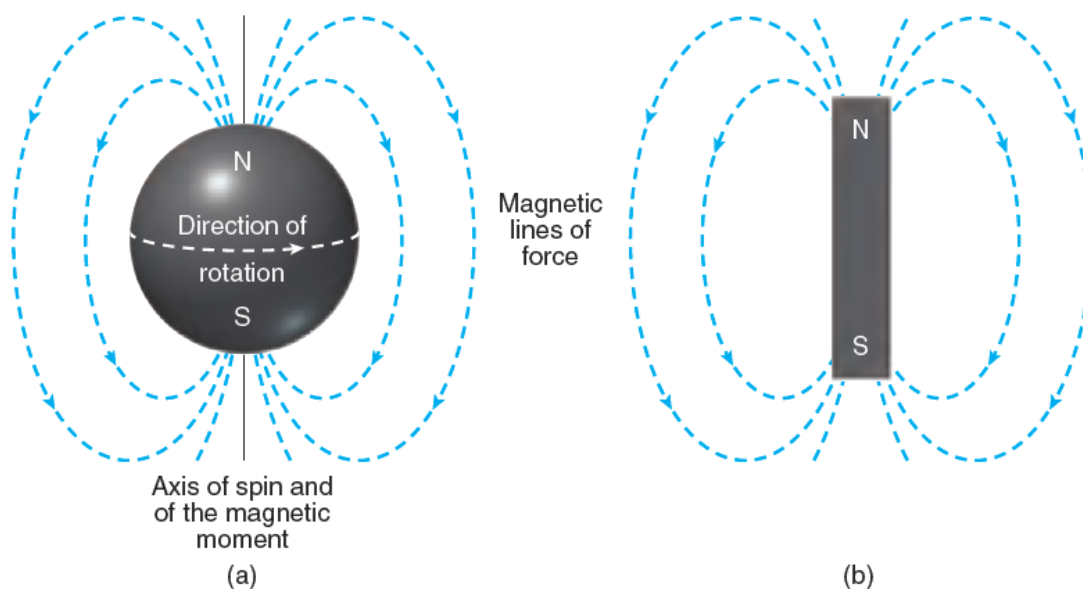


# AN INTRODUCTION TO NMR SPECTROSCOPY

NMR spectroscopy was developed by physicists in the late 1940s to study the properties of atomic nuclei. In 1951, chemists realized that NMR spectroscopy could also be used to study the structures of organic compounds.

Nuclei that have an odd number of protons or an odd number of neutrons (or both) have a property called spin that allows them ( $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{15}\text{N}$ ,  $^{19}\text{F}$ , and  $^{31}\text{P}$ ) to be studied by NMR. Nuclei such as  $^{12}\text{C}$  and  $^{16}\text{O}$  do not have spin and therefore cannot be studied by NMR. Because hydrogen nuclei (protons) were the first nuclei studied by NMR, the acronym NMR is generally assumed to mean  $^1\text{H}$  NMR (proton magnetic resonance). A spinning proton can be viewed as a rotating sphere of charge, which generates a magnetic field called a magnetic moment. The magnetic moment of a spinning proton is similar to the magnetic field produced by a bar magnet (Figure 1).



In the absence of an applied magnetic field, the magnetic moments of the nuclei are randomly oriented

However, when placed between the poles of a strong magnet, the magnetic moments of the nuclei align either *with or against* the applied magnetic field (Figure 2).

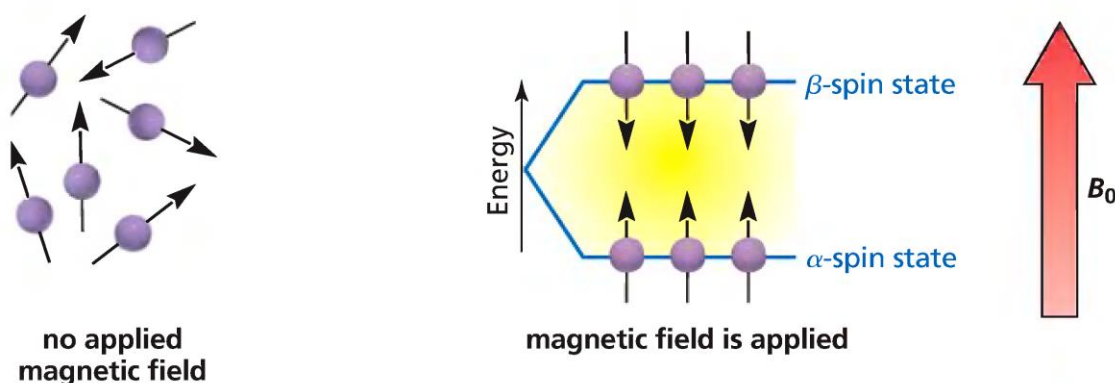
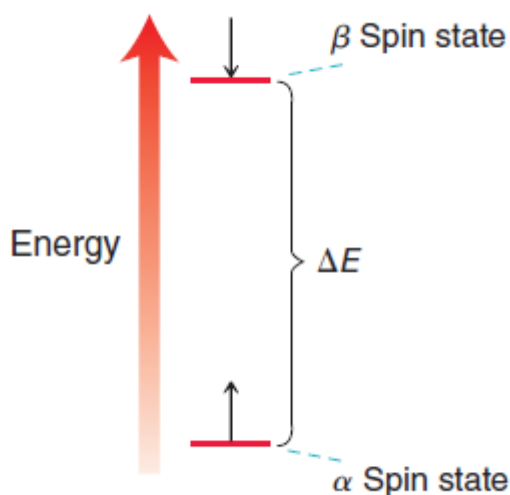


Figure 2

In the absence of an applied magnetic field, the magnetic moments of the nuclei are randomly oriented. In the presence of an applied magnetic field, the magnetic moments of the nuclei line up with (the  $\alpha$ -spin state) or against (the  $\beta$ -spin state) the applied magnetic field.

Nuclei with magnetic moments that align with the field are in the lower-energy  $\alpha$ -spin state, whereas those with magnetic moments that align against the field are in the higher-energy  $\beta$ -spin state. The  $\beta$ -spin state is higher in energy because more energy is needed to align the magnetic moments against the field than with it. As a result, more nuclei are in the  $\alpha$ -spin state. The difference in the populations is very small (about 20 out of 1 million protons), but it is sufficient to form the basis of NMR spectroscopy.

The energy difference ( $\Delta E$ ) between the  $\alpha$ - and  $\beta$ -spin states depends on the strength of the applied magnetic field ( $B_0$ ): the greater the strength of the applied magnetic field, the greater the  $\Delta E$  (Figure 3).



When a sample is subjected to a pulse of radiation whose energy corresponds to the difference in energy ( $\Delta E$ ) between the  $\alpha$ - and  $\beta$ -spin states, nuclei in the  $\alpha$ -spin state are promoted to the  $\beta$ -spin state. This transition is called "flipping" the spin.

With currently available magnets, the energy difference between the  $\alpha$ - and  $\beta$ -spin states is small, so only a small amount of energy is needed to flip the spin. The radiation used to supply this energy is in the radio frequency (rf) region of the electromagnetic spectrum and is called rf radiation. When the nuclei absorb rf radiation and flip their spins, they generate signals whose frequency depends on the difference in energy ( $\Delta E$ ) between the  $\alpha$ - and  $\beta$ -spin states. The NMR spectrometer detects these signals and plots their frequency versus their intensity; this plot is an NMR spectrum.

The nuclei are said to be in resonance with the rf radiation, hence the term nuclear magnetic resonance. In this context, "resonance" refers to the nuclei flipping back and forth between  $\alpha$ - and  $\beta$ -spin states in response to the rf radiation.

The following equation shows that the energy difference between the spin states ( $\Delta E$ ) depends on the operating frequency of the spectrometer ( $\nu$ ), which depends, in turn, on the strength of the magnetic field ( $B_0$ ), measured in tesla (T), and the gyromagnetic ratio ( $\gamma$ );  $h$  is Planck's constant.

$$\Delta E = h\nu = h \frac{\gamma}{2\pi} B_0$$

The gyromagnetic ratio is a constant that depends on the particular kind of nucleus. In the case of a proton,  $\gamma = 26.75 \times 10^7 \text{ T}^{-1} \text{ s}^{-1}$ ; in the case of a  $^{13}\text{C}$  nucleus, it is  $6.688 \times 10^7 \text{ T}^{-1} \text{ s}^{-1}$ .

Canceling Planck's constant on both sides of the equation gives:

$$\nu = \frac{\gamma}{2\pi} B_0$$

The following calculation shows that if an  $^1\text{H}$  NMR spectrometer is equipped with a magnet that generates a magnetic field of 7.046 T, then the spectrometer will require an operating frequency of 300 MHz (megahertz):

$$\begin{aligned} \nu &= \frac{\gamma}{2\pi} B_0 \\ &= \frac{2.675 \times 10^8}{2(3.1416)} \text{ T}^{-1} \text{ s}^{-1} \times 7.046 \text{ T} \\ &= 300 \times 10^6 \text{ Hz} = 300 \text{ MHz} \end{aligned}$$

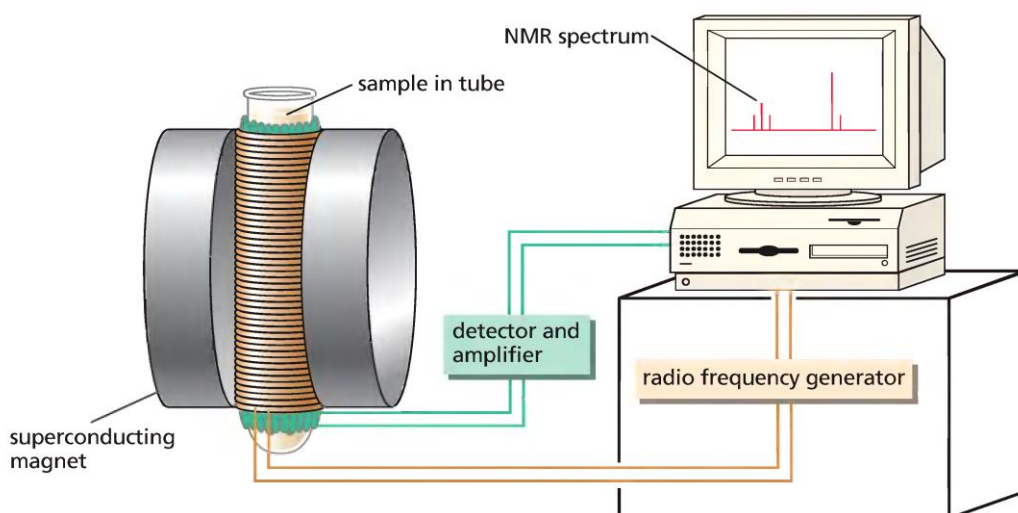
**PROBLEM 1:** What frequency (in MHz) is required to cause a proton to flip its spin when it is exposed to a magnetic field of 1 T?

**PROBLEM 2:** a. Calculate the magnetic field (in tesla) required to flip an  $^1\text{H}$  nucleus in an NMR spectrometer that operates at 360 MHz.

b. What strength magnetic field is required when a 500-MHz instrument is used for  $^1\text{H}$  NMR?

## NMR Spectrometers

To obtain an NMR spectrum, a small amount of a compound is dissolved in about 0.5 mL of solvent. This solution is put into a long, thin glass tube, which is then placed within a powerful magnetic field (Figure 4). Spinning the sample tube about its long axis averages the position of the molecules in the magnetic field, which increases the resolution of the spectrum.



In modern instruments called pulsed Fourier transform (FT) spectrometers, the magnetic field is held constant and an rf pulse of short duration excites all the protons simultaneously. The rf pulse covers a range of frequencies, so each nucleus can absorb the frequency it requires to come into resonance (flip its spin) and produce a signal—called a free induction decay (FID)—at a frequency corresponding to  $\Delta E$ . The intensity of the FID signal decays as the nuclei lose the energy they gained from the rf pulse.

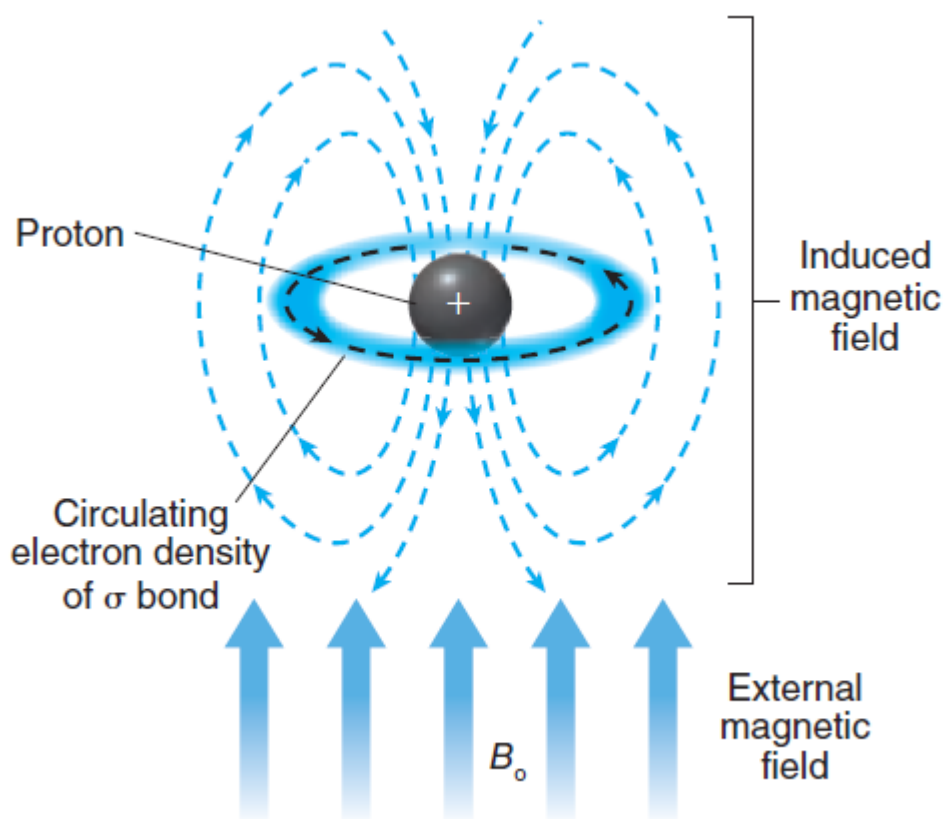
## SHIELDING CAUSES DIFFERENT HYDROGENS TO SHOW SIGNALS AT DIFFERENT FREQUENCIES

We have seen that the frequency of an NMR signal depends on the strength of the magnetic field experienced by the nucleus (Figure 2). Therefore, if all the hydrogens in a compound were to experience the same magnetic field, they would all give signals of the same frequency. If this were the case, all NMR spectra would consist of one signal, which would tell us nothing about the structure of the compound, except that it contains hydrogens.

A nucleus, however, is embedded in a cloud of electrons that partly shields it from the applied magnetic field. Fortunately for chemists, the shielding varies for different hydrogens in a molecule. In other words, all the hydrogens do not experience the same magnetic field.

What causes shielding? In a magnetic field, the electrons circulate about the nuclei and induce a local magnetic field that acts in opposition to the applied magnetic field and, therefore, subtracts from it. As a result, the effective magnetic field—the amount of magnetic field that the nuclei actually "sense" through the surrounding electrons—is somewhat smaller than the applied magnetic field:

$$B_{\text{effective}} = B_{\text{applied}} - B_{\text{local}}$$



This means that the greater the electron density of the environment in which the proton is located, the more the proton is shielded from the applied magnetic field and the greater  $B_{\text{local}}$ . This type of shielding is called diamagnetic shielding.

Thus, protons in electron-rich environments sense *a smaller effective magnetic field*.

Therefore, they require a lower frequency to come into resonance—that is, flip their spin—because  $\Delta E$  is smaller (Figure 2). Protons in electron-poor environments sense a larger effective magnetic field and so require a higher frequency to come into resonance because  $\Delta E$  is larger.

An NMR spectrum exhibits a signal for each proton in a different environment.

Protons in electron-rich environments are more shielded and appear at lower frequencies (on the right-hand side of the spectrum; Figure 5). Protons in electron-poor environments are less shielded and appear at higher frequencies (on the left-hand side of the spectrum). Notice that high frequency in an NMR spectrum is on the left-hand side, just as it is in IR and UV/Vis spectra.

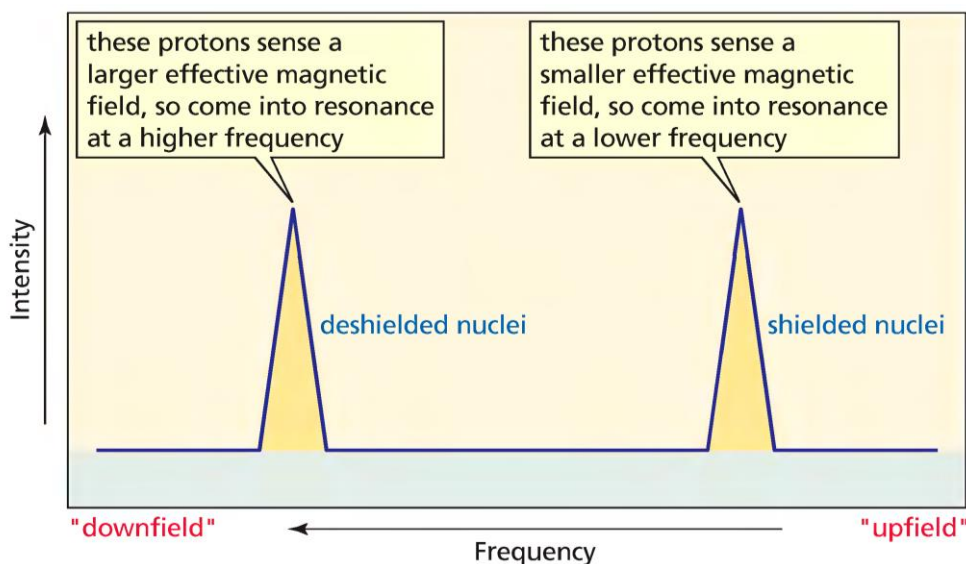


Figure 5

## Preparing the Sample

In order to acquire a  $^1\text{H}$  NMR (called a “proton NMR”) spectrum of a compound, the compound is usually dissolved in a solvent and placed in a narrow glass tube, which is then inserted into the NMR spectrometer. If the solvent itself has protons, the spectrum will be overwhelmed with signals from the solvent, rendering it unreadable. As a result, solvents without protons must be used. Although there are several solvents that lack protons, such as  $\text{CCl}_4$ , these solvents do not dissolve all compounds. In practice, deuterated solvents are generally used.

## Characteristics of a $^1\text{H}$ NMR Spectrum

The spectrum produced by  $^1\text{H}$  NMR spectroscopy is generally rich with information that can be interpreted to determine a molecular structure.

- 1-The first valuable piece of information is the number of signals.
- 2-The *location* of each signal indicates the electronic environment of the protons giving rise to the signal.
3. The *area* under each signal indicates the number of protons giving rise to the signal.
4. The *shape* of the signal indicates the number of neighboring protons.

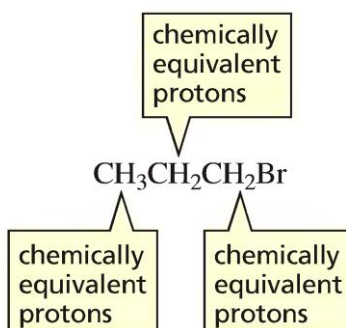
## 1- Number of Signals

### Chemical Equivalence

The number of signals in a  $^1\text{H}$  NMR spectrum indicates the number of different kinds of protons (protons in different electronic environments).

- Protons that occupy identical electronic environments are called **chemically equivalent**, and they will produce only one signal.

For example: 1-bromopropane has three different sets of chemically equivalent protons: the three methyl protons are chemically equivalent, the two methylene ( $\text{CH}_2$ ) protons on the middle carbon are chemically equivalent; and the two methylene protons on the carbon bonded to the bromine make up the third set of protons.

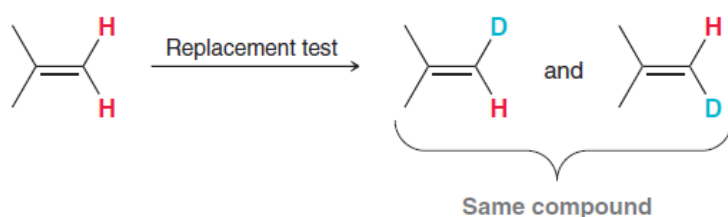


Each set of chemically equivalent protons in a compound produces a separate signal in its  $^1\text{H}$  NMR spectrum. Thus, 1-bromopropane has three signals in its  $^1\text{H}$  NMR spectrum because it has three sets of chemically equivalent protons.



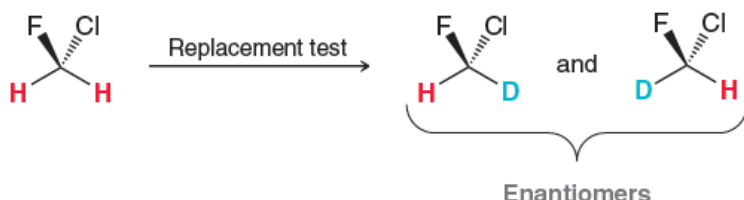
2-Bromopropane has two sets of chemically equivalent protons, so it has two signals in its  $^1\text{H}$  NMR spectrum. The six methyl protons are equivalent so they produce only one signal, and the hydrogen bonded to the middle carbon gives the second signal. chemically equivalent protons.

the two protons on the middle carbon of propane is a simple method, called the **replacement test**, Draw the compound two times, each time replacing one of the protons with deuterium; for example:



Then, determine the relationship between the two drawings. If they represent the same compound, then the protons are homotopic.

Draw the compound two times, each time replacing one of the protons with deuterium; for example:

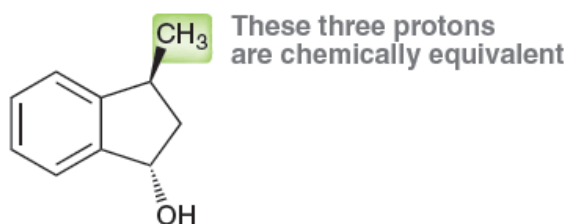


Then, determine the relationship between the two drawings. If they represent enantiomers, then the protons are **enantiotopic**.

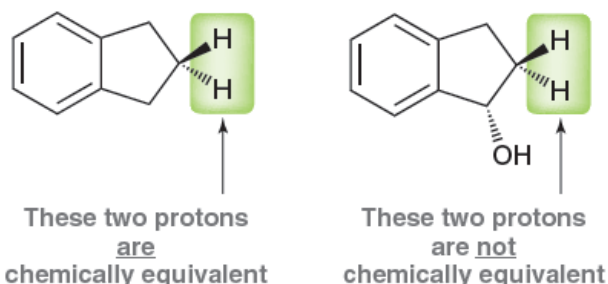
**Homotopic Protons and enantiotopic protons are chemically equivalent.**

In general, it is possible to determine the number of expected signals for a compound using a few simple rules:

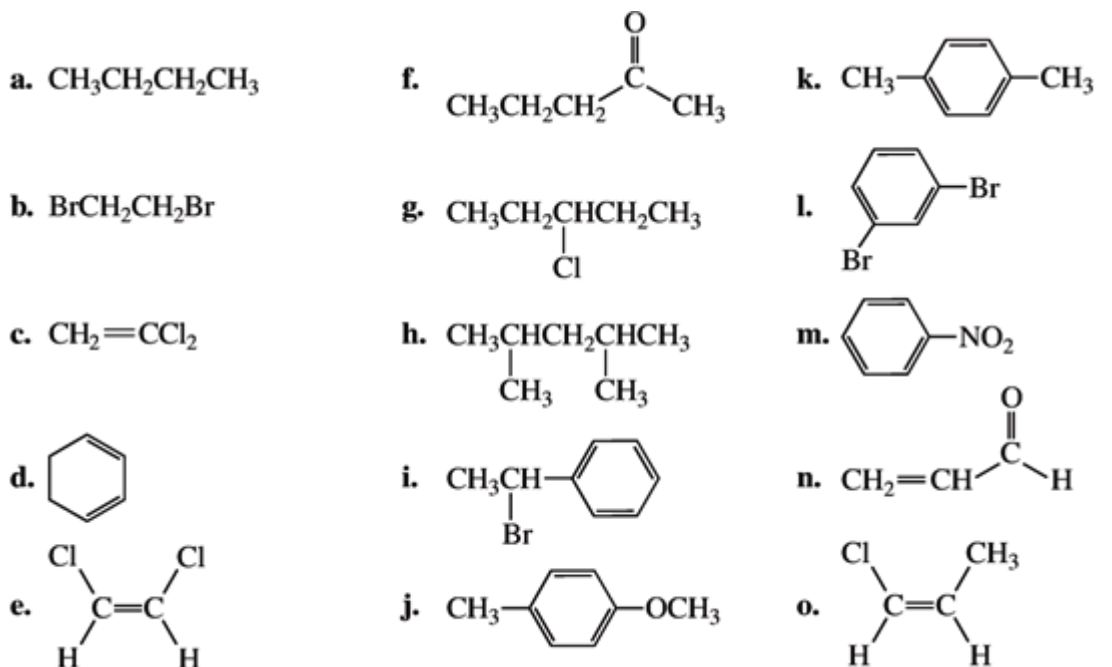
- The three protons of a  $\text{CH}_3$  group are always chemically equivalent.



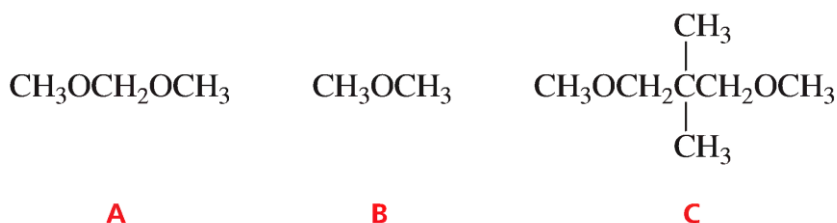
- The two protons of a CH<sub>2</sub> group will generally be chemically equivalent if the compound has no chirality centers. If the compound has a chirality center, then the protons of a CH<sub>2</sub> group will generally not be chemically equivalent. Examples:



How many signals would you expect to see in the <sup>1</sup>H NMR spectrum of each of the following compounds?



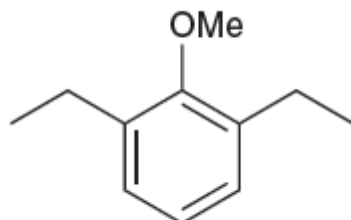
How could you distinguish the <sup>1</sup>H NMR spectra of the following compounds?



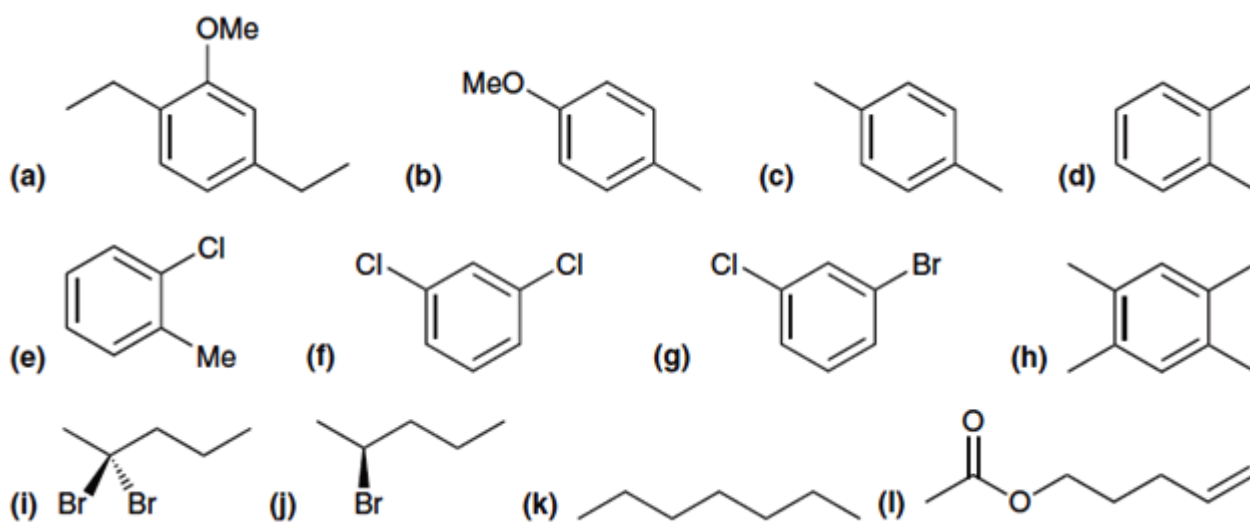
- (c) How many different kinds of protons are present in pentane?
- (d) How many different kinds of protons are present in hexane?
- (e) How many different kinds of protons are present in 1-chlorohexane?

- Identify the structure of a compound with molecular formula  $C_5H_{12}$  that exhibits only one kind of proton. That is, all 12 protons are chemically equivalent.

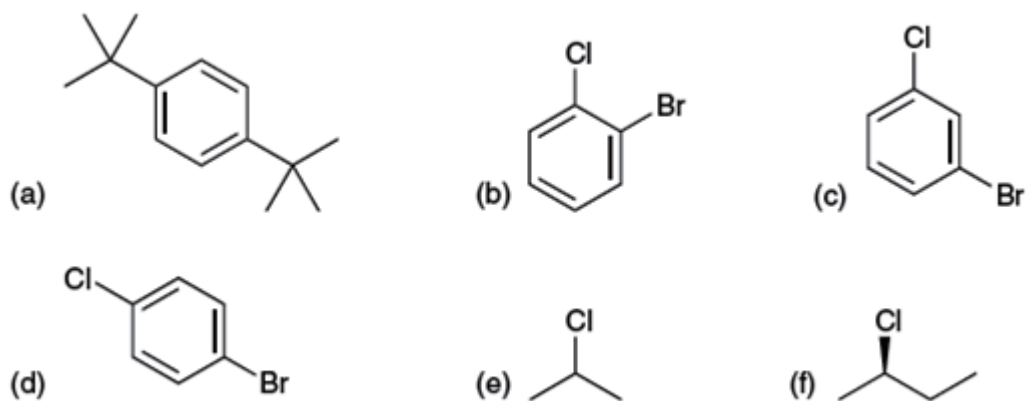
Identify the number of signals expected in the  $^1H$  NMR spectrum of the following compound:



Identify the number of signals expected in the  $^1H$  NMR spectrum of each of the following compounds:

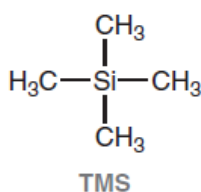


How many signals would you expect in the  $^1H$  NMR spectrum of each of the following compounds:



## Chemical shift

The location of the signal, called its chemical shift ( $\delta$ ), which is defined relative to the frequency of absorption of a reference compound, tetramethylsilane (TMS). In practice, deuterated solvents used for NMR spectroscopy typically contain a small amount of TMS, which produces a signal at a lower frequency than the signals produced by most organic compounds.



The frequency of each signal is then described as the difference (in hertz) between the resonance frequency of the proton being observed and that of TMS divided by the operating frequency of the spectrometer: tetramethylsilane (TMS) is used a reference because:

- it is highly volatile (bp = 26.5 °C),
- it can easily be removed from the sample by evaporation after the NMR spectrum.
- The methyl protons of TMS are in a more electron-rich environment than are most protons in organic molecules because silicon is less electronegative than carbon (their electronegativities are 1.8 and 2.5, respectively). Consequently, the signal for the methyl protons of TMS is at a lower frequency than most other signals (that is, the TMS signal appears to the right of the other signals).

The most common scale for chemical shifts is the  $\delta$  (delta) scale. The TMS signal defines the zero position on the  $\delta$  scale

$$\delta = \frac{\text{observed shift from TMS in hertz}}{\text{operating frequency of the instrument in hertz}}$$

The advantage of the  $\delta$  scale is that the chemical shift is independent of the operating

frequency of the NMR spectrometer. when benzene is analyzed using an NMR spectrometer operating at 300 MHz, the protons of benzene absorb a frequency of rf radiation that is 2181 Hz larger than the frequency of absorption of TMS. The chemical shift of these protons is then calculated in the following way:

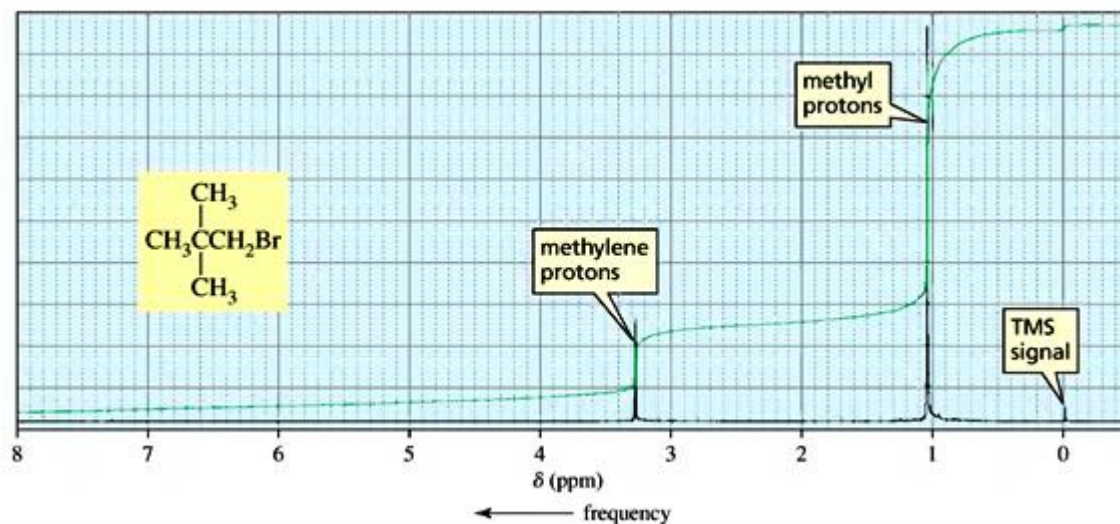
$$\delta = \frac{2181 \text{ Hz}}{300 \times 10^6 \text{ Hz}} = 7.27 \times 10^{-6}$$

If a 60-MHz spectrometer is used instead, the protons of benzene absorb a frequency of rf radiation that is 436 Hz larger than the frequency of absorption of TMS. The chemical shift of these protons is then calculated in the following way:

$$\delta = \frac{436 \text{ Hz}}{60 \times 10^6 \text{ Hz}} = 7.27 \times 10^{-6}$$

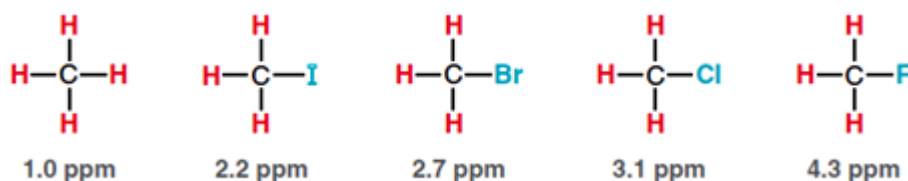
Notice that the chemical shift of the protons is a constant, regardless of the operating frequency of the spectrometer signals on the left side of the spectrum (downfield) are “high-frequency signals” because they result from deshielded protons that absorb higher frequencies of rf radiation. In contrast, signals on the right side of the spectrum (upfield) are “low-frequency signals” because they result from shielded protons that absorb lower frequencies of rf radiation.

Remember that the right-hand side of an NMR spectrum is the low-frequency side, where protons in electron-rich environments (more shielded) show a signal. The left-hand side is the high-frequency side, where protons in electron-poor environments (less shielded) show a signal (Figure 6)

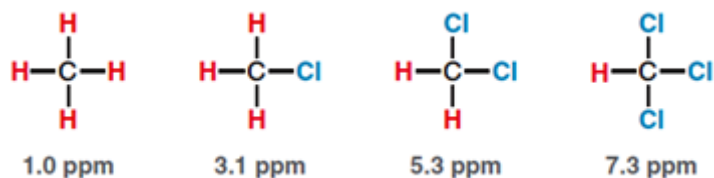


## Inductive Effects

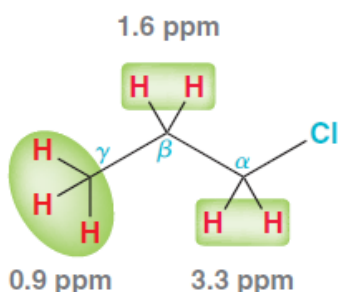
electronegative atoms, such as halogens, withdraw electron density from neighboring atoms. This inductive effect causes the protons of the methyl group to be deshielded (surrounded by less electron density), and as a result, the signal produced by these protons appears at a higher chemical shift than the protons of an alkane. The strength of this effect depends on the electronegativity of the halogen. Compare the chemical shifts of the protons in the following compounds:



Fluorine is the most electronegative element and therefore produces the strongest effect. When multiple halogens are present, the effect is additive, as can be seen when comparing the following compounds:



Each chlorine atom adds approximately 2 ppm to the chemical shift of the signal. The inductive effect tapers off drastically *بضمحل بشكل كبير* with distance, as can be seen by comparing the chemical shifts of the protons in 1-chloropropane.



The effect is most significant for the protons at the alpha position. The protons at the beta position are only slightly affected, and the protons at the gamma position are virtually unaffected by the presence of the chlorine atom.

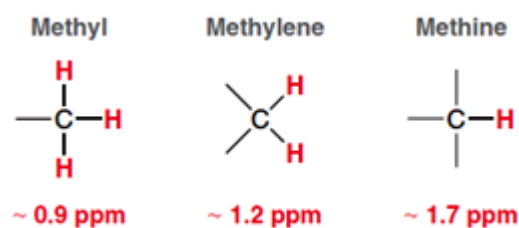
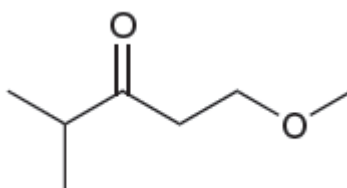


Table 1 shows the effect of a few functional groups on the chemical shifts of alpha protons

| FUNCTIONAL GROUP  | EFFECT ON ALPHA PROTONS | EXAMPLE   |
|---|-------------------------|---|
| Oxygen of an alcohol or ether   | +2.5                    | <p>Methylene group (CH<sub>2</sub>) = 1.2 ppm<br/>Next to oxygen = +2.5 ppm<br/><b>3.7 ppm</b></p> <p>Actual chemical shift = 3.7 ppm</p>         |
| Oxygen of an ester  | +3                      | <p>Methylene group (CH<sub>2</sub>) = 1.2 ppm<br/>Next to oxygen = +3.0 ppm<br/><b>4.2 ppm</b></p> <p>Actual chemical shift = 4.1 ppm</p>         |
| Carbonyl group (C=O)<br>All carbonyl groups, including ketones, aldehydes, esters, etc. | +1                      | <p>Methylene group (CH<sub>2</sub>) = 1.2 ppm<br/>Next to carbonyl group = +1.0 ppm<br/><b>2.2 ppm</b></p> <p>Actual chemical shift = 2.4 ppm</p> |

- The effect on beta protons is generally about one-fifth of the effect on the alpha protons. For example, in an alcohol, the presence of an oxygen atom adds +2.5 ppm to the chemical shift of the alpha protons but adds only +0.5 ppm to the beta protons. Similarly, a carbonyl group adds +1 ppm to the chemical shift of the alpha protons but only +0.2 to the beta protons

**Q:** Predict the chemical shifts for the signals in the <sup>1</sup>H NMR spectrum of the following compound:

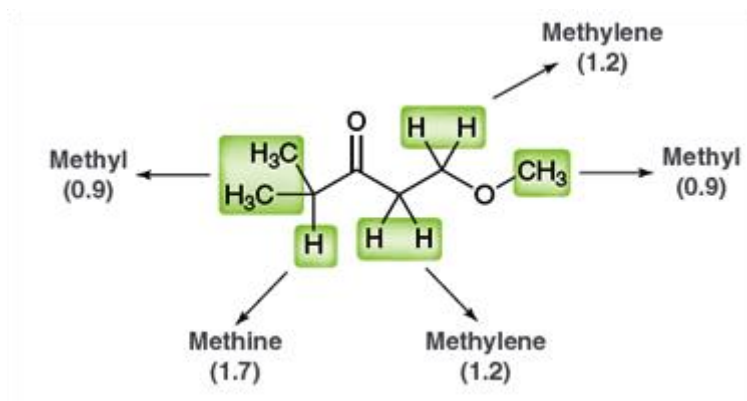


Solution

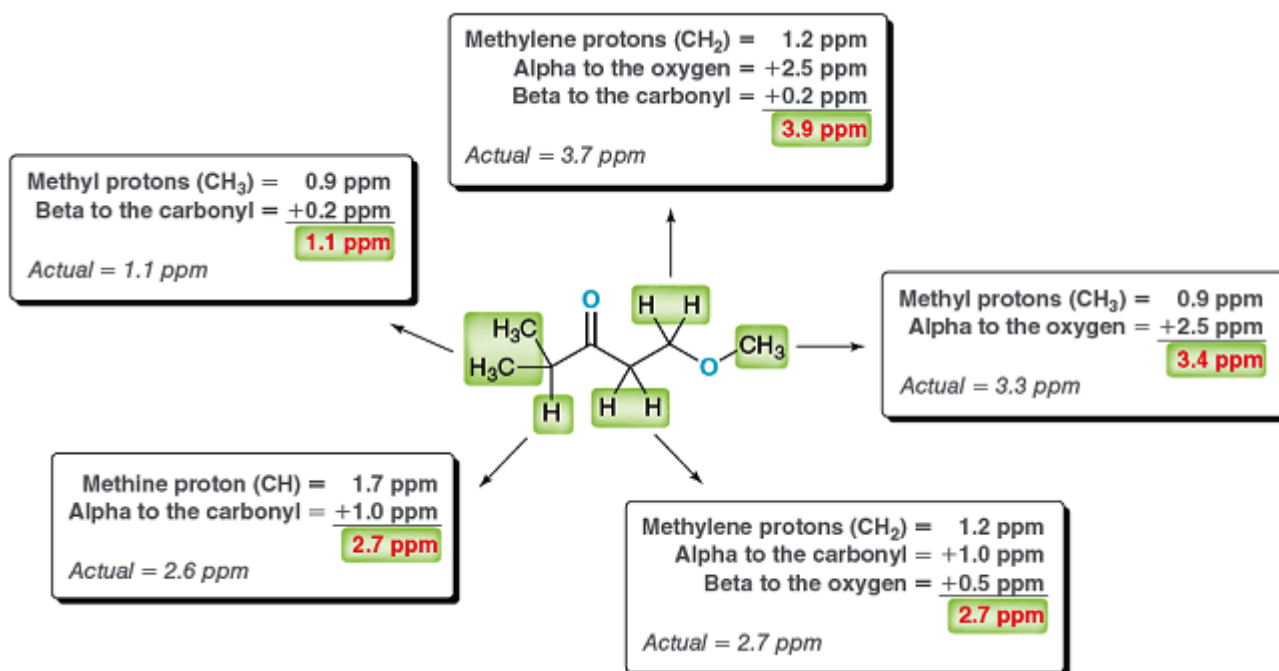
First determine the total number of expected signals.

In this compound, there are five different kinds of protons, giving rise to five distinct signals.

- For each type of signal, identify whether it represents methyl (0.9 ppm), methylene (1.2 ppm), or methine (1.7 ppm) groups.

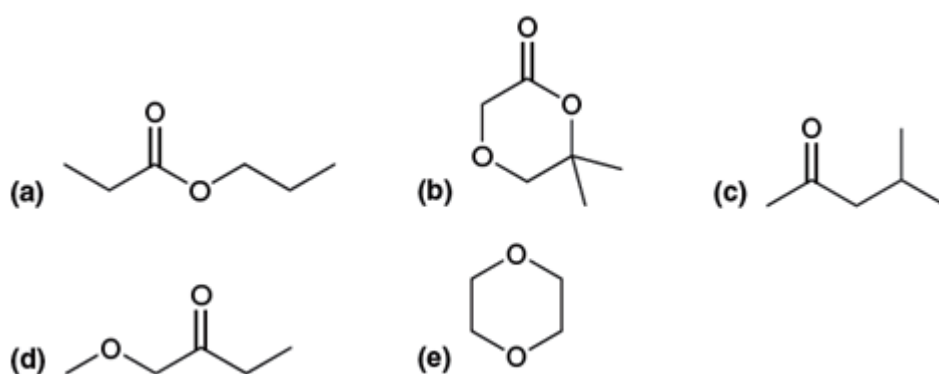


Finally, modify each of these numbers based on proximity to oxygen and the carbonyl group.



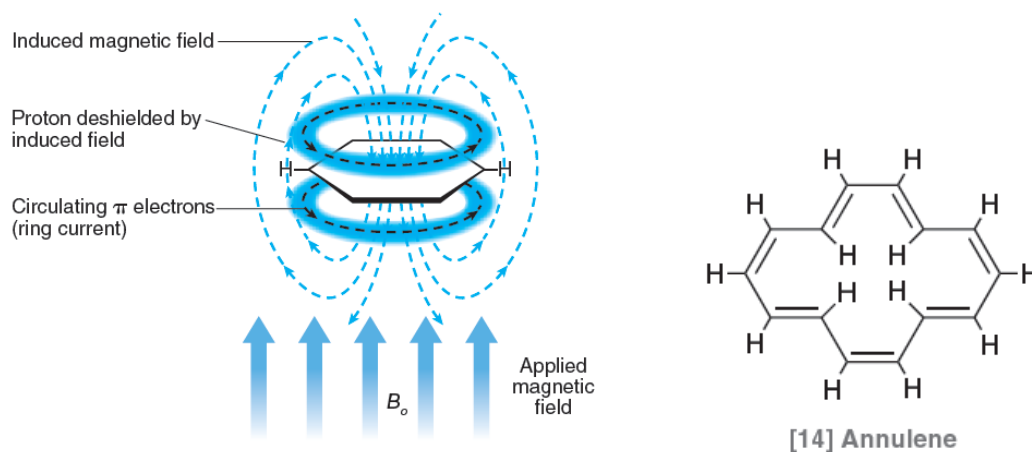
**Q:** Predict the chemical shifts for the signals in the <sup>1</sup>H NMR spectrum of each of the following compounds:





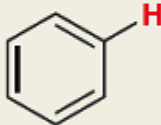
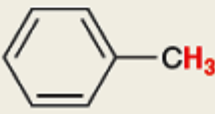
## Anisotropic Effects

The chemical shift of a proton is also sensitive to diamagnetic effects that result from the motion of nearby p electrons. As an example, when benzene is placed in a strong magnetic field. The magnetic field causes the p electrons to circulate, and this flow of electrons creates an induced, local magnetic field. The result is diamagnetic anisotropy, which means that different regions of space are characterized by different magnetic field strengths.

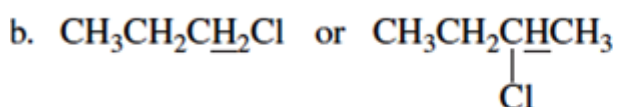
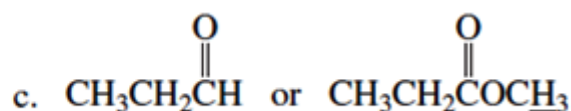
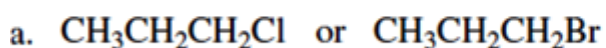
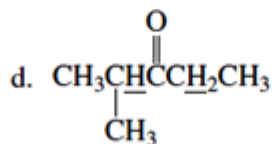
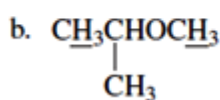
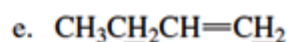
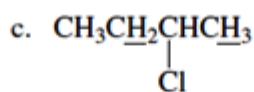
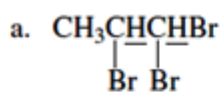


Locations inside the ring are characterized by a local magnetic field that opposes the external field, while locations outside the ring are characterized by a local magnetic field that adds to the external field. The protons connected to the ring are permanently positioned outside of the ring, and as a result, they experience a stronger magnetic field. These protons experience the external magnetic field plus the local magnetic field. All p bonds exhibit a similar anisotropic effect. That is, p electrons circulate under the influence of an external magnetic field, generating a local magnetic field.

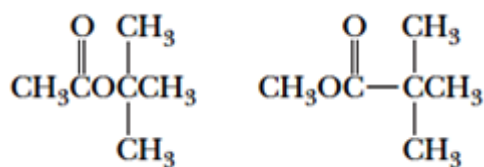
For each type of p bond, the precise location of the nearby protons determines their chemical shift. For example, aldehydic protons produce characteristic signals at approximately 10 ppm. Table 2 summarizes important chemical shifts.

| TYPE OF PROTON  | CHEMICAL SHIFT ( $\delta$ )   | TYPE OF PROTON  | CHEMICAL SHIFT ( $\delta$ )   |
|-----------------|---|-----------------|---|
| Methyl          | $R-CH_3$<br>~0.9  | Alkyl halide    | $R-\overset{H}{\underset{R}{\overset{R}{C}}}-X$<br>2-4                                      |
| Methylene       | $\text{>}CH_2$<br>~1.2  | Alcohol         | $R-O-H$<br>2-5  |
| Methine         | $-CH-$<br>~1.7  | Vinyl           | $=CH_2$<br>4.5-6.5  |
| Allylic         | $CH_2=CH-CH_2-H$<br>~2  | Aryl            | <br>6.5-8 |
| Alkynyl         | $R-C\equiv C-H$<br>~2.5   | Aldehyde        | $R-\overset{O}{\parallel}C-H$<br>~10  |
| Aromatic methyl | <br>~2.5 | Carboxylic acid | $R-\overset{O}{\parallel}C-O-H$<br>~12  |

Q: In each of the following pairs of compounds, which of the underlined protons has the greater chemical shift

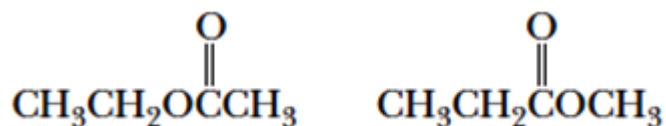


Q: Following are structural formulas for two constitutional isomers with the molecular formula  $C_6H_{12}O_2$



Show how you can distinguish between these isomers on the basis of chemical shift.

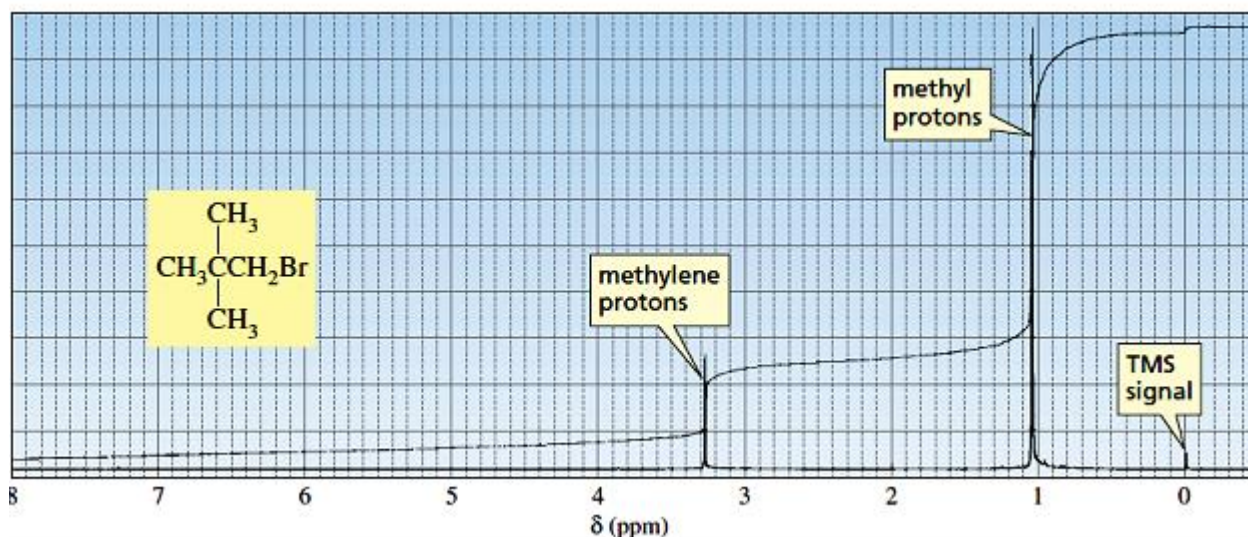
Q: Following are two constitutional isomers with the molecular formula  $C_4H_8O_2$



Show how you can distinguish between these isomers on the basis of chemical shift.

### Integration

the area under each signal is proportional to the number of protons that gives rise to the signal



the area under a curve can be determined by integration.

An NMR spectrometer is equipped with a computer that calculates the integrals electronically.

Modern spectrometers print out the integrals as numbers on the spectrum.

The integrals can also be displayed by a line of integration.

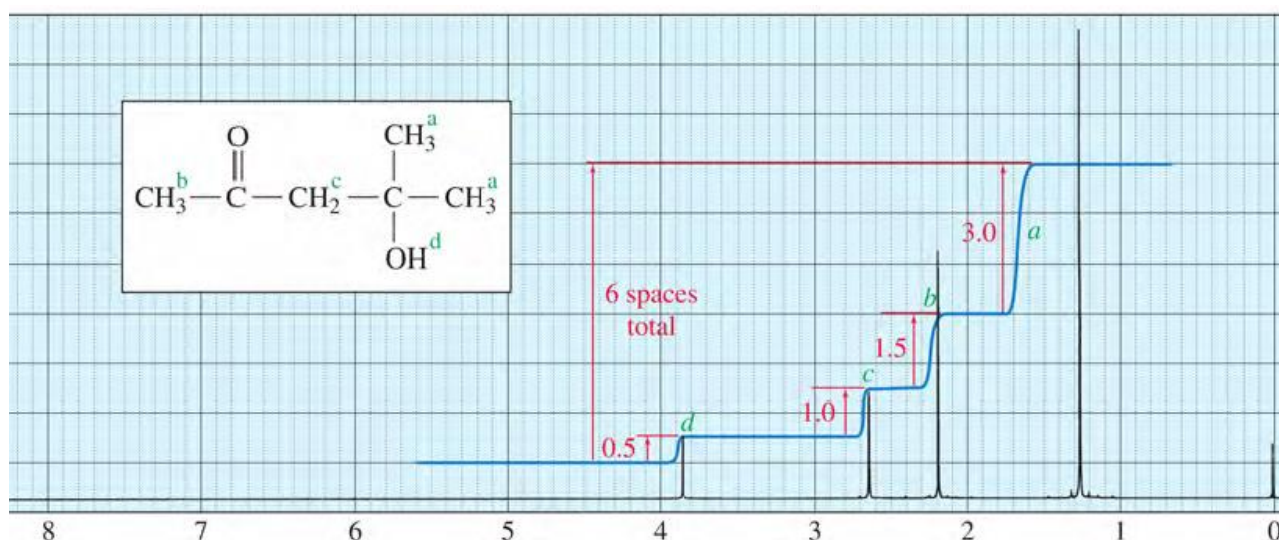
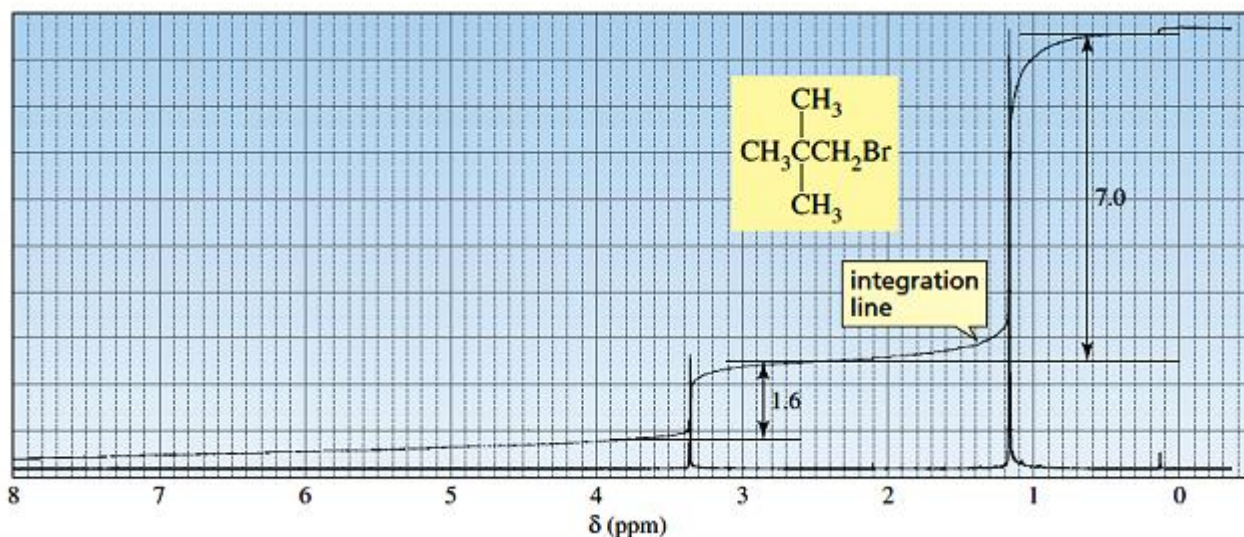
The height of each integration step is proportional to the area under that signal, which, in turn, is proportional to the number of protons giving rise to the signal.

By measuring the heights of the integration, In order to convert these numbers into useful information,

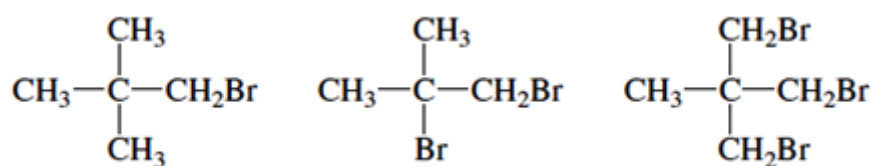
- choose the smallest number (1.6 in this case) and then divide all integration values by this number:  $1.6 : 7.0 = 1 : 4.4$

In order to arrive at whole numbers (there is no such thing as half a proton), multiply all the numbers by 2, so the ratio of protons in the compound is  $2 : 8.8$ , which is rounded to  $2 : 9$ .

The integration tells us the relative number of protons that give rise to each signal, not the absolute number. For example, integration could not distinguish between 1,1-dichloroethane and 1,2-dichloro-2-methylpropane because both compounds would show an integral ratio of  $1 : 3$ .



How would integration distinguish the NMR spectra of the following compounds?



Calculate the ratios of the different kinds of protons in a compound with an integral ratio of 6 : 4 : 18.4.

b. Determine the structure of a compound that would give these relative integrals in the observed order

Divide each by the smallest number:

$$\frac{6}{4} = 1.5$$

$$\frac{4}{4} = 1$$

$$\frac{18.4}{4} = 4.6$$

Multiply by a number that will cause all the numbers to be close to whole numbers:

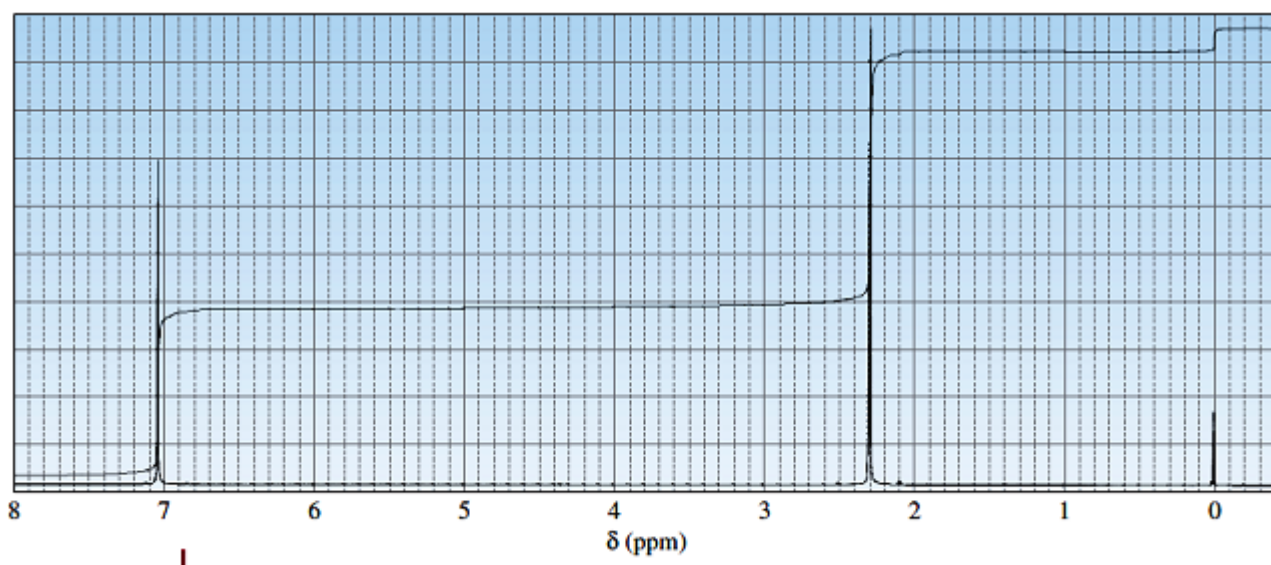
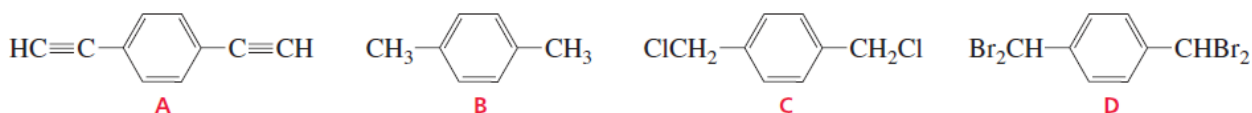
The ratio gives the relative numbers of the different kinds of protons. The actual ratio could be or even some higher multiple, but let's not go there if we don't have to.

b. The "3" suggests a methyl, the "2" a methylene, and the "9" a tert-butyl. The methyl is closest to a group causing deshielding, and the tert-butyl group is farthest away from the group causing deshielding. The following compound meets these requirements:

PROBLEM :

The NMR spectrum shown in the following Figure corresponds to one of the following compounds.

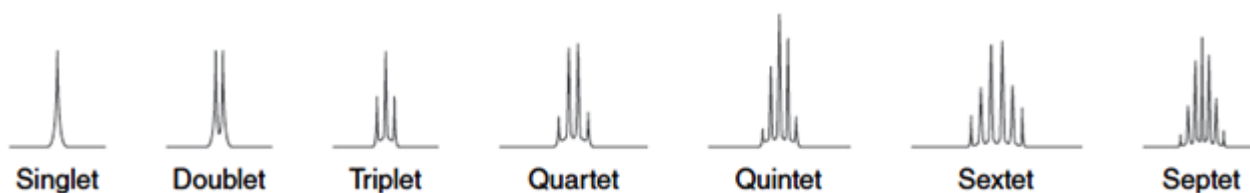
Which compound is responsible for this spectrum?



### Multiplicity (Coupling)

multiplicity is defined by the number of peaks in the signal.

A *singlet* has one peak, a *doublet* has two peaks, a *triplet* has three peaks, a *quartet* has four peaks, a *quintet* has five peaks, and so on.

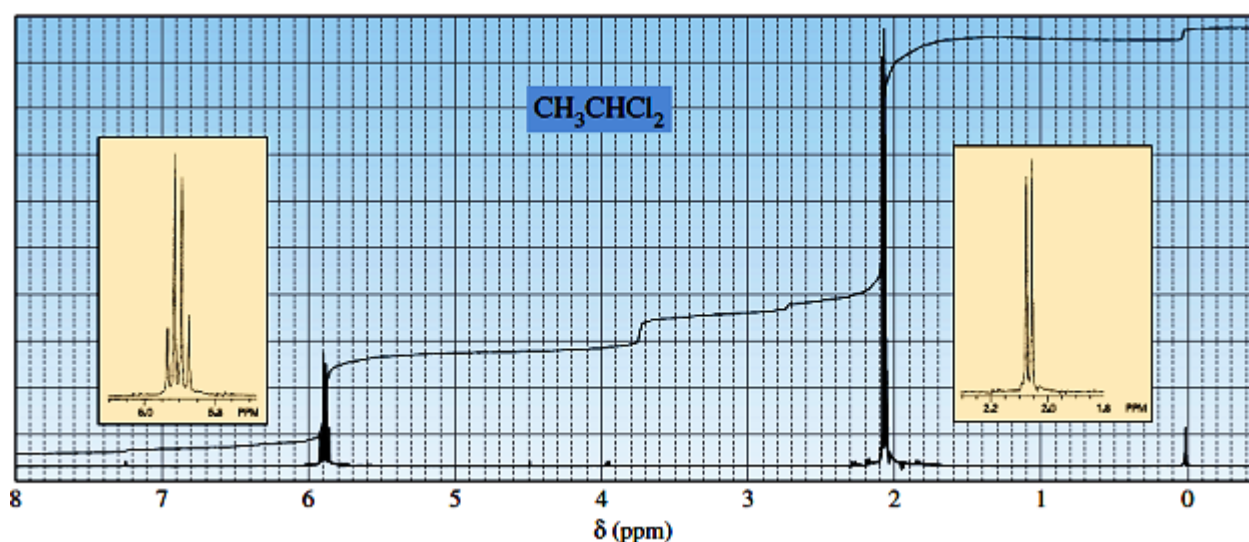


Splitting is caused by protons bonded to adjacent (i.e., directly attached) carbons.

The splitting of a signal is described by the  $N+1$  rule where  $N$  is the number of equivalent protons bonded to adjacent carbons.

Splitting is always mutual: If the  $a$  protons split the  $b$  protons, then the  $b$  protons must split the  $a$  protons.

Coupled protons split each other's signal.

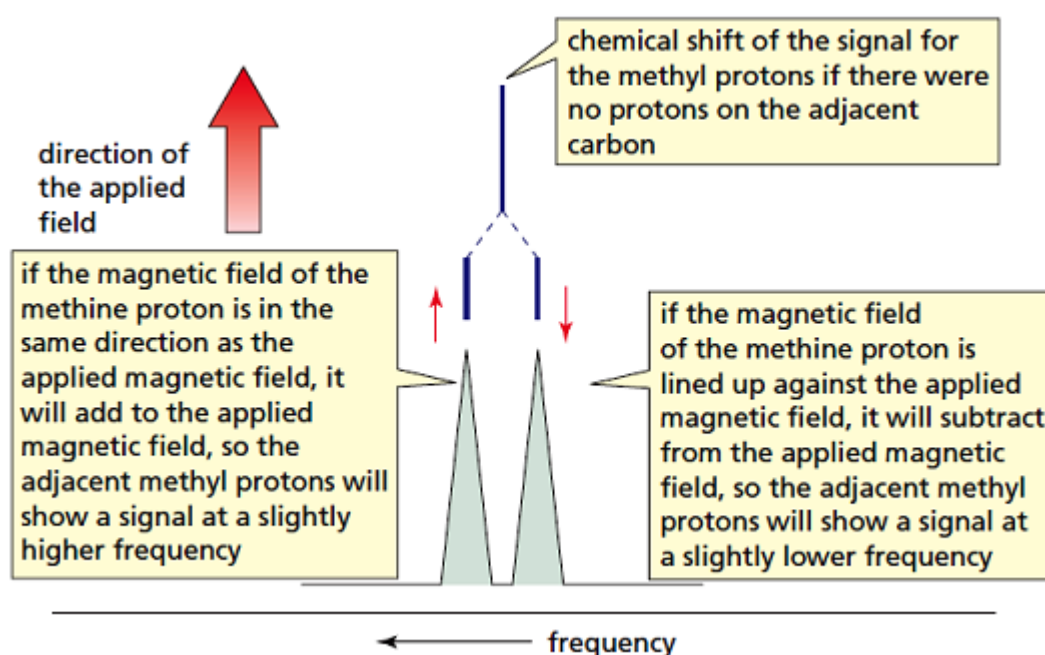


There are two major factors that determine whether or not splitting occurs:

**1. Equivalent protons do not split each other.** Consider the two methylene groups in 1,2-dichloroethane. All four protons are chemically equivalent, and therefore, they do not split each other. In order for splitting to occur, the neighboring protons must be different than the protons producing the signal.

For example, the methyl protons of 1,1-dichloroethane  $\text{CH}_3\text{CHCl}_2$  show a signal is influenced by the magnetic field of the methine proton. If the magnetic field of the methine proton aligns with that of the applied magnetic field, it

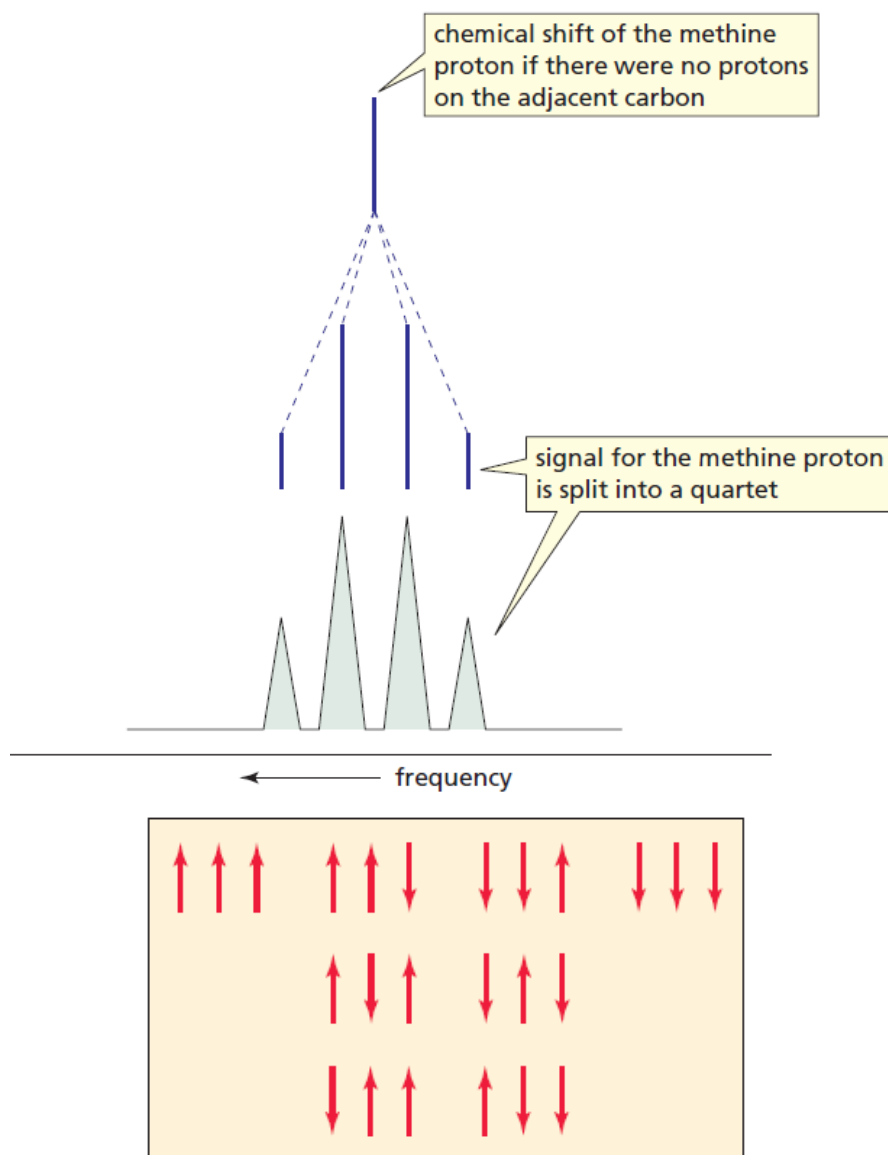
will add to the applied magnetic field, causing the methyl protons to show a signal at a slightly higher frequency. On the other hand, if the magnetic field of the methine proton aligns against the applied magnetic field, it will subtract from the applied magnetic field and the methyl protons will show a signal at a lower frequency. Therefore, the signal for the methyl protons is split into two peaks, one corresponding to the higher frequency and one corresponding to the lower frequency. Because each spin state has almost the same population, about half the methine protons are lined up with the applied magnetic field and about half are lined up against it. Therefore, the two peaks of the doublet have approximately the same height and area.



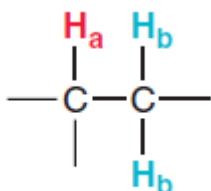
Similarly, the frequency at which the methine proton shows a signal is influenced by the magnetic fields of the three protons bonded to the adjacent carbon. The magnetic fields of each of the three methyl protons can align with the applied magnetic field, two can align with the field and one against it, one can align with it and two against it, or all three can align against it. Because the magnetic field that the methine proton senses is affected in four different ways, its signal is a quartet. The relative intensities of the peaks in a signal reflect the number of ways the neighboring protons can be aligned relative to the applied magnetic field. For example, a quartet has relative peak intensities of 1 : 3 : 3 : 1 because there is only



one way to align the magnetic fields of three protons so that they are all with the field and only one way to align them so that they are all against the field.



Now consider a scenario in which  $H_a$  has two neighboring protons.



The chemical shift of  $H_a$  is impacted by the presence of both  $H_b$  protons, each of which can be aligned either with or against the external field. Once again, each  $H_b$  is like a tiny magnet and has an impact on the chemical shift of  $H_a$ . In each molecule,  $H_a$  can find itself in one of three possible electronic environments, resulting in a triplet

(Figure 16.11). If each peak of the triplet is separately integrated, a ratio of 1 : 2 : 1 is observed, consistent with statistical expectations.

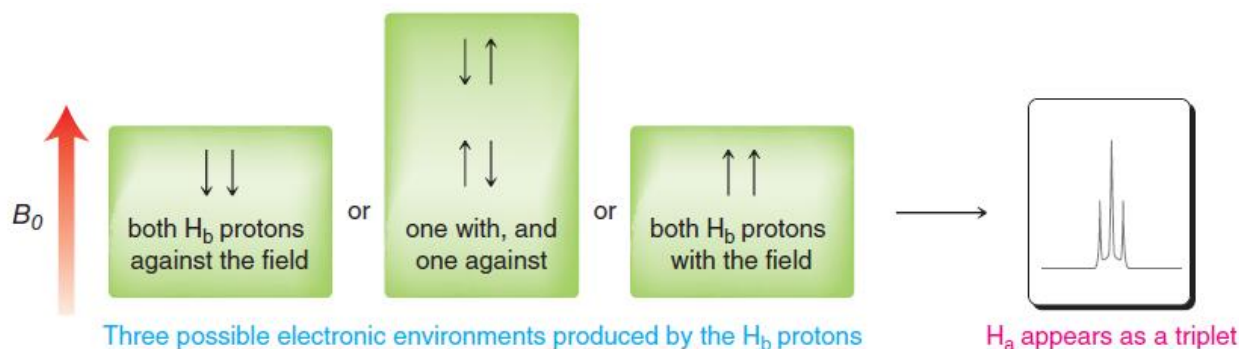
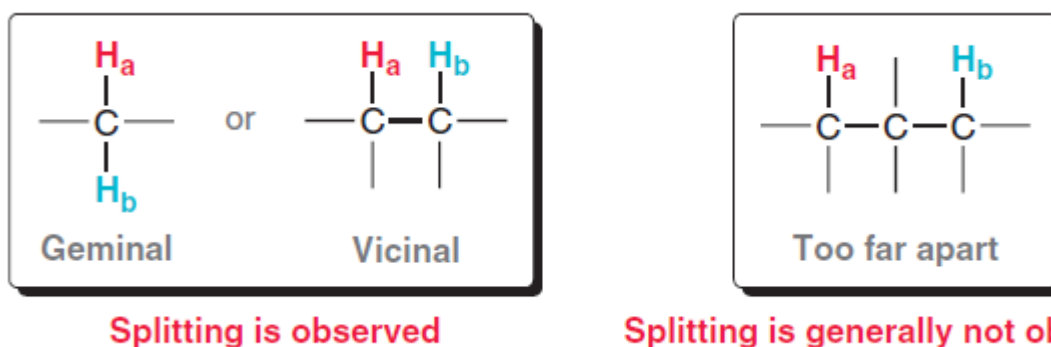


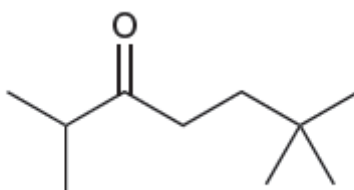
table 3 multiplicity indicates the number of neighboring protons

| NUMBER OF NEIGHBORS | MULTIPLICITY | RELATIVE INTENSITIES OF INDIVIDUAL PEAKS |
|---------------------|--------------|--|
| 1                   | Doublet      | 1:1                                      |
| 2                   | Triplet      | 1:2:1                                    |
| 3                   | Quartet      | 1:3:3:1                                  |
| 4                   | Quintet      | 1:4:6:4:1                                |
| 5                   | Sextet       | 1:5:10:10:5:1                            |
| 6                   | Septet       | 1:6:15:20:15:6:1                         |

2. Splitting is most commonly observed when protons are separated by either two or three s bonds; that is, when the protons are either diastereotopic protons on the same carbon atom (geminal) or connected to adjacent carbon atoms (vicinal).

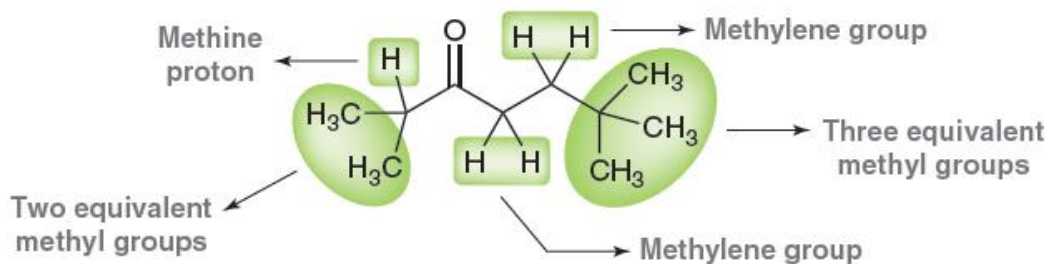


Determine the multiplicity of each signal in the expected  $^1H$  NMR spectrum of the following compound:



Step 1

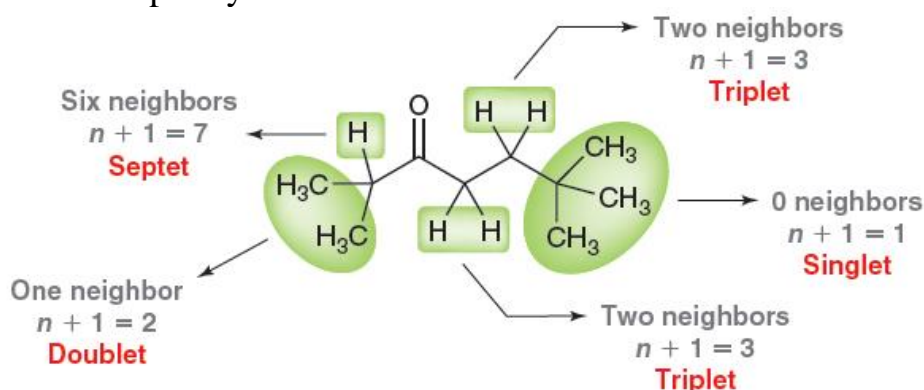
Identify all of the different kinds of protons.



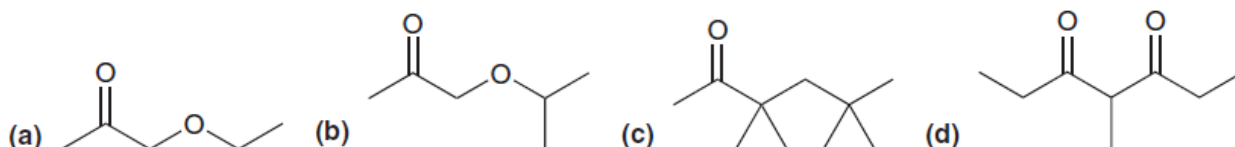
Step 2

For each kind of proton, identify the number of neighbors (n).

The multiplicity will follow the  $n + 1$

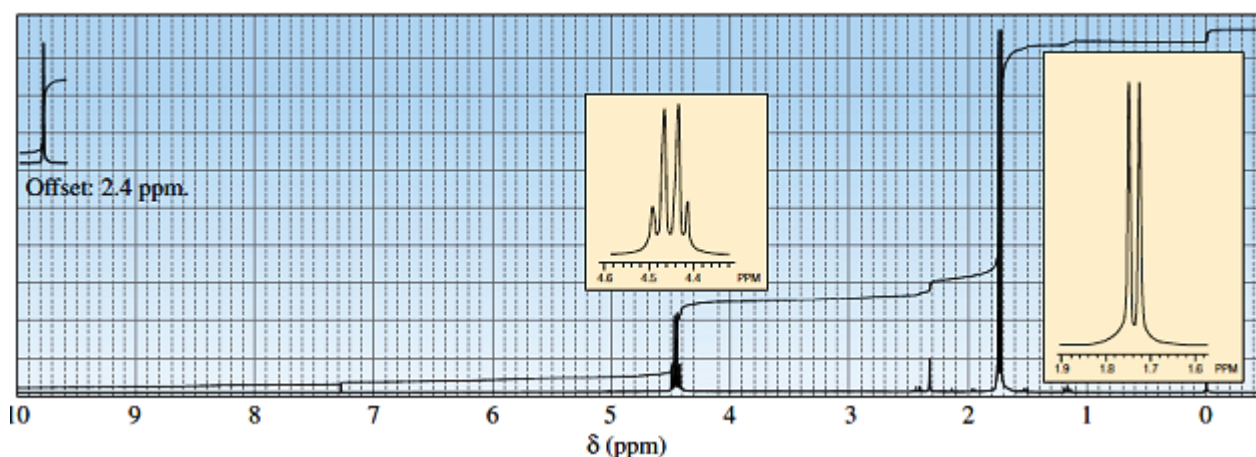


For each of the following compounds, determine the multiplicity of each signal in the expected  $^1\text{H}$  NMR spectrum:

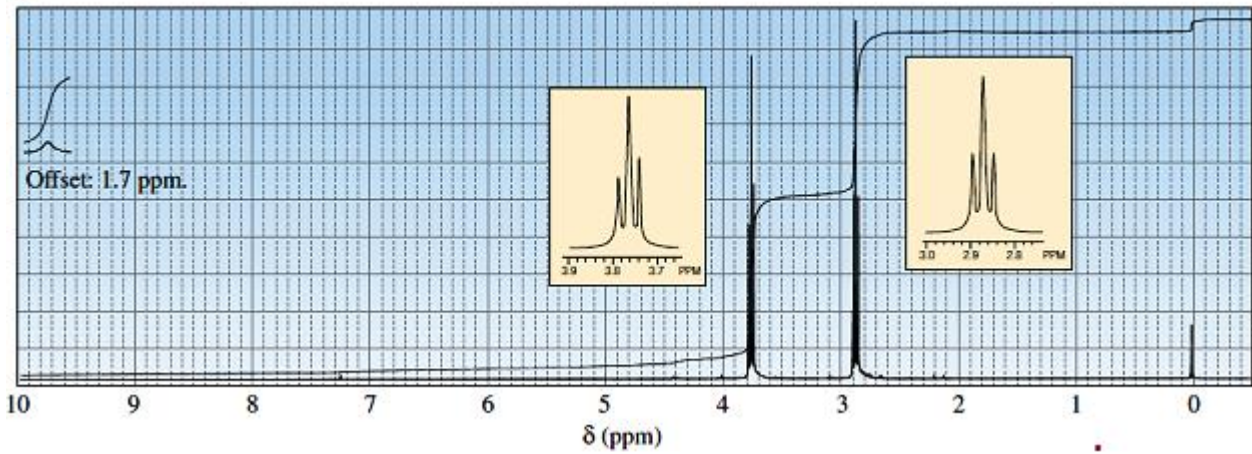


The NMR spectra of two carboxylic acids with molecular formula are  $\text{C}_3\text{H}_5\text{O}_2\text{Cl}$  shown in Figure 14.14. Identify the carboxylic acids. (The “offset” notation means that the signal has been moved to the right by the indicated amount).

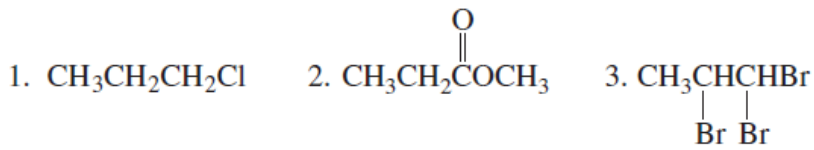
a.



b.

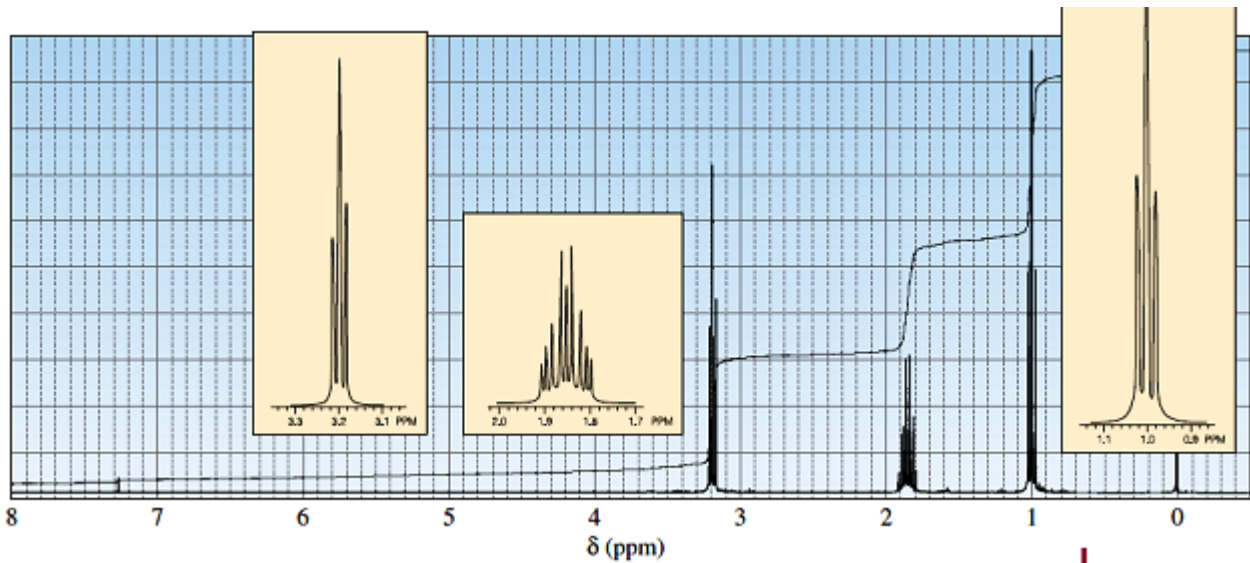


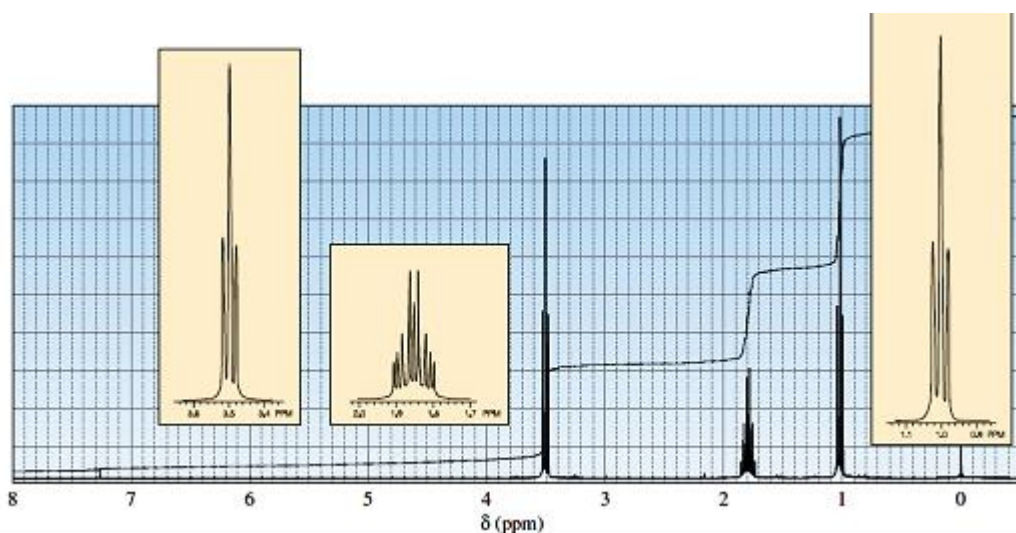
Which set of protons in each of the following compounds is the least shielded?



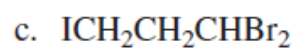
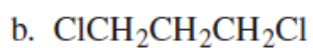
b. Which set of protons in each compound is the most shielded?

One of the spectra in Figure () is due to 1-chloropropane, and the other to 1-iodopropane. Which is which?

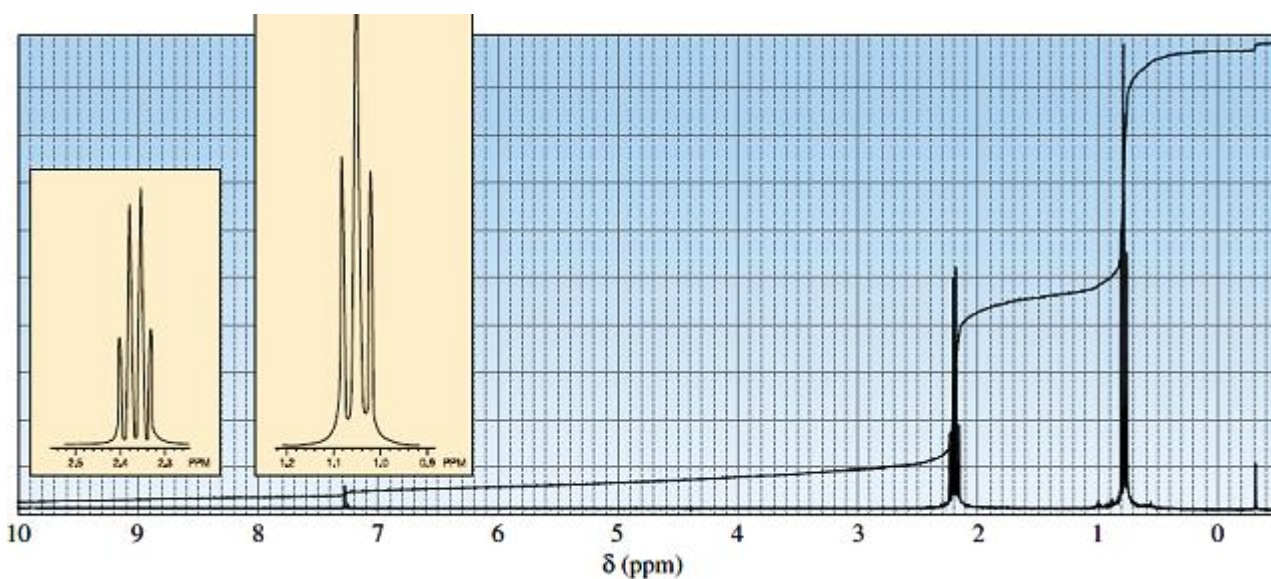
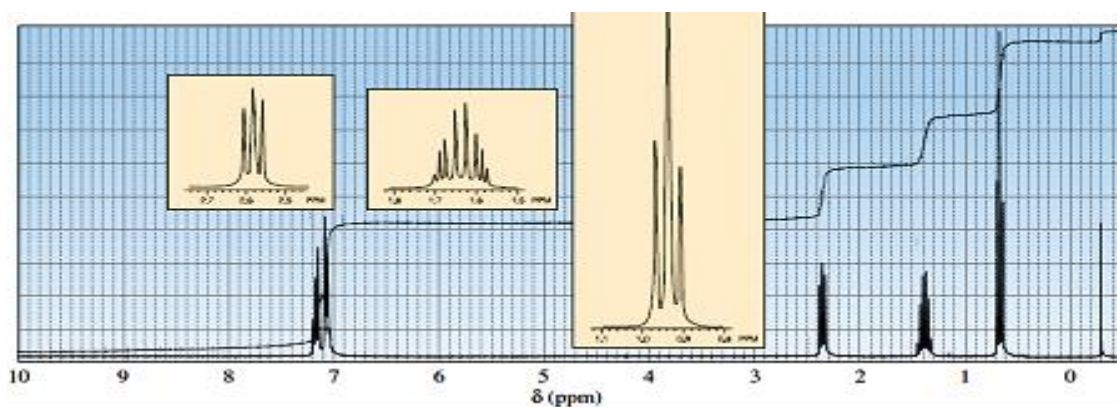


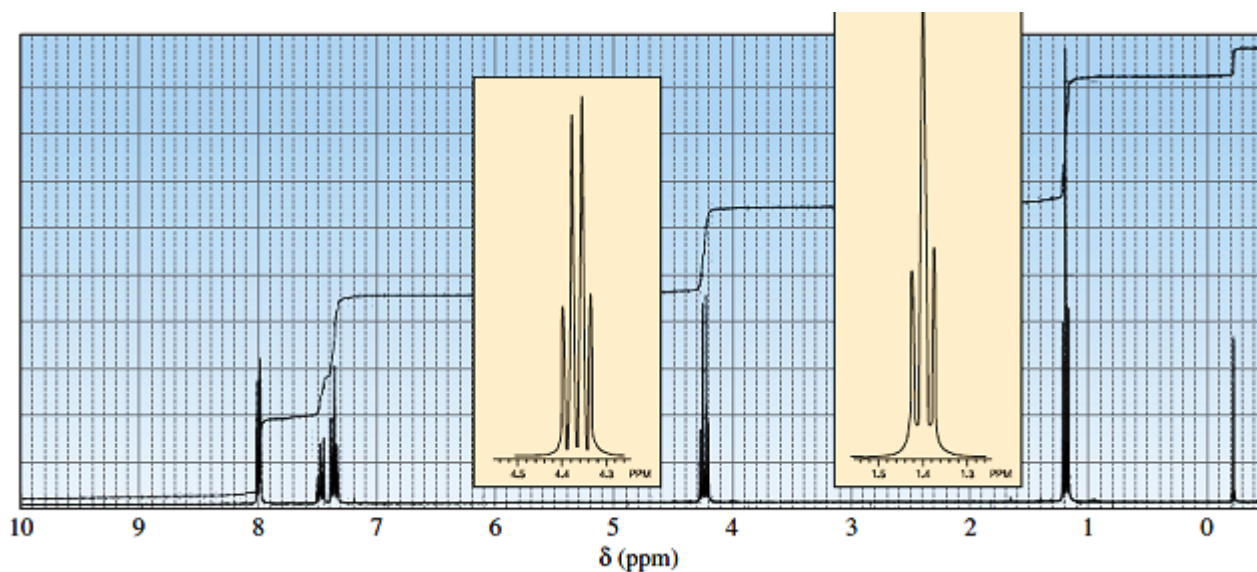


Indicate the number of signals and the multiplicity of each signal in the  $^1\text{H}$  NMR spectrum of each of the following compounds:



Identify each compound from its molecular formula and its  $^1\text{H}$  NMR spectrum:

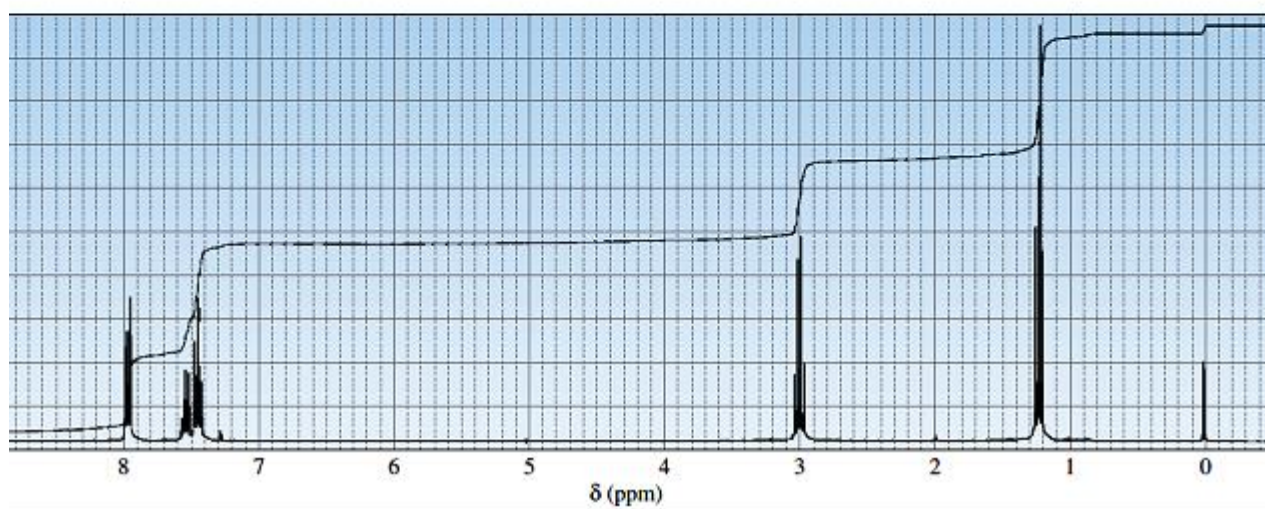
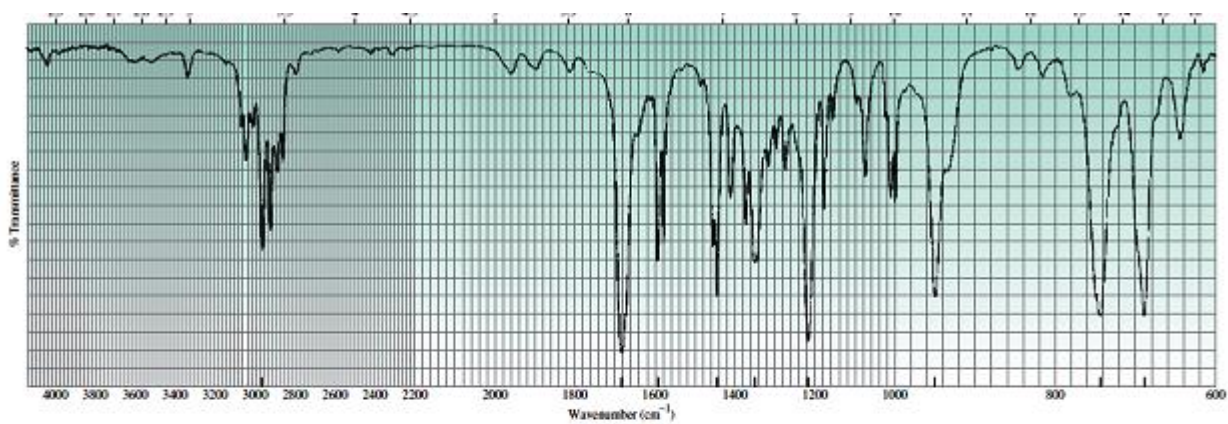




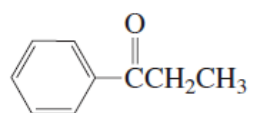
Identify the following compounds. (Relative integrals are given from left to right across the spectrum.)

- The  $^1\text{H}$  NMR spectrum of a compound with molecular formula  $C_4H_{10}O_2$  has two singlets with an area ratio of 2 : 3
- The  $^1\text{H}$  NMR spectrum of a compound with molecular formula  $C_6H_{10}O_2$  has two singlets with an area ratio of 2 : 3
- The  $^1\text{H}$  NMR spectrum of a compound with molecular formula  $C_8H_6O_2$  has two singlets with an area ratio of 1 : 2.

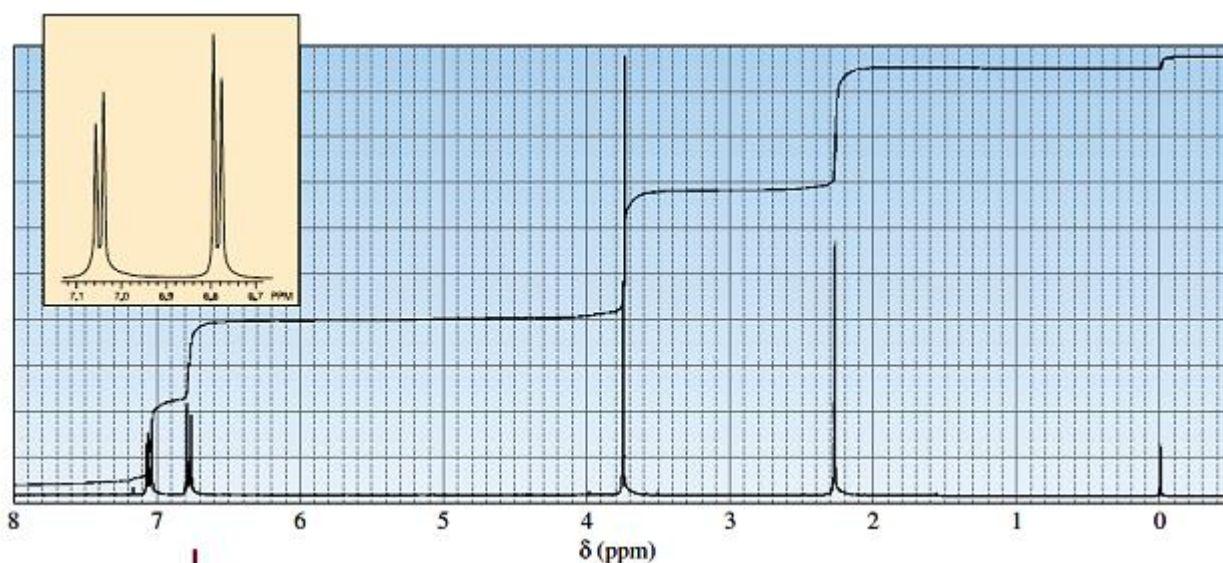
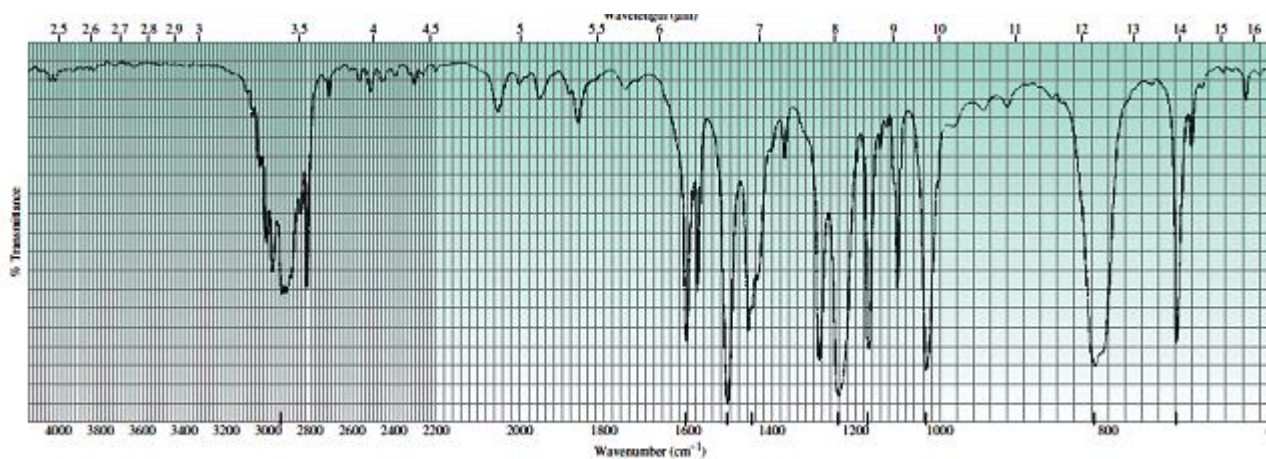
Identify the compound with molecular formula  $C_9H_{10}O$  that gives the IR and  $^1\text{H}$  NMR spectra in Figure



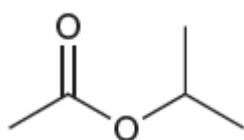
Answer:



$C_8H_{10}O$

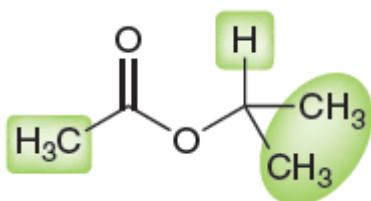


Draw the expected  $^1\text{H}$  NMR spectrum of isopropyl acetate.



Solution

Begin by determining the number of signals:



Begin by determining the number of signals:

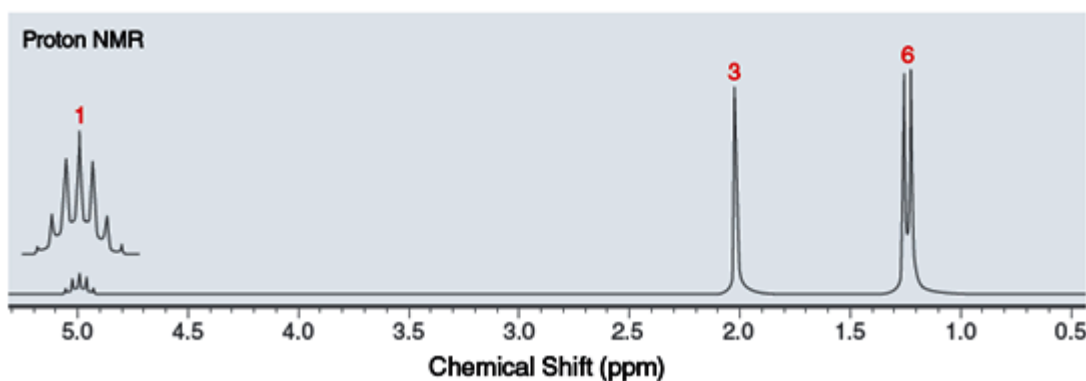
This compound is expected to produce three signals in its  $^1\text{H}$  NMR spectrum. For each signal, determine its chemical shift, integration and multiplicity. Let's begin with the methyl group on the left side of the molecule. A methyl group is expected to



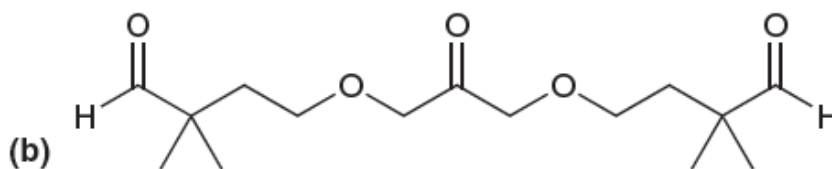
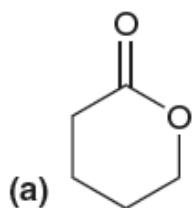
produce a signal at 0.9 ppm, and the neighboring carbonyl group adds +1, so we expect the signal to appear at approximately 1.9 ppm. The integration should be 3, because there are three protons (I = 3H). The multiplicity should be a singlet, because there are no neighbors.

Now consider the signal of the methine proton on the right. The benchmark value for a methine proton is 1.7 ppm, and the neighboring oxygen atom adds +3, so we expect the signal to appear at 4.7 ppm. The integration should be 1, because there is one proton (I = 1H). The multiplicity should be a septet, because there are six neighbors.

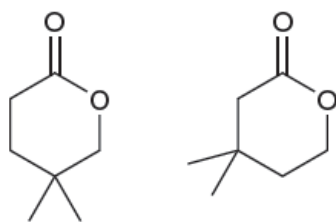
The last signal is from the two methyl groups on the right. Methyl groups have a benchmark value of 0.9 ppm, and the distant oxygen atom adds +0.6, so we expect a signal at approximately 1.5 ppm. The integration should be 6 because there are six protons (I = 6H), and the multiplicity should be a doublet because there is only one neighbor. This information enables us to draw the expected <sup>1</sup>H NMR



Draw the expected <sup>1</sup>H NMR spectrum for each of the following compounds:

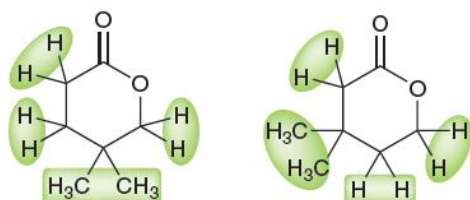


How would you use <sup>1</sup>H NMR spectroscopy to distinguish between the following compounds?

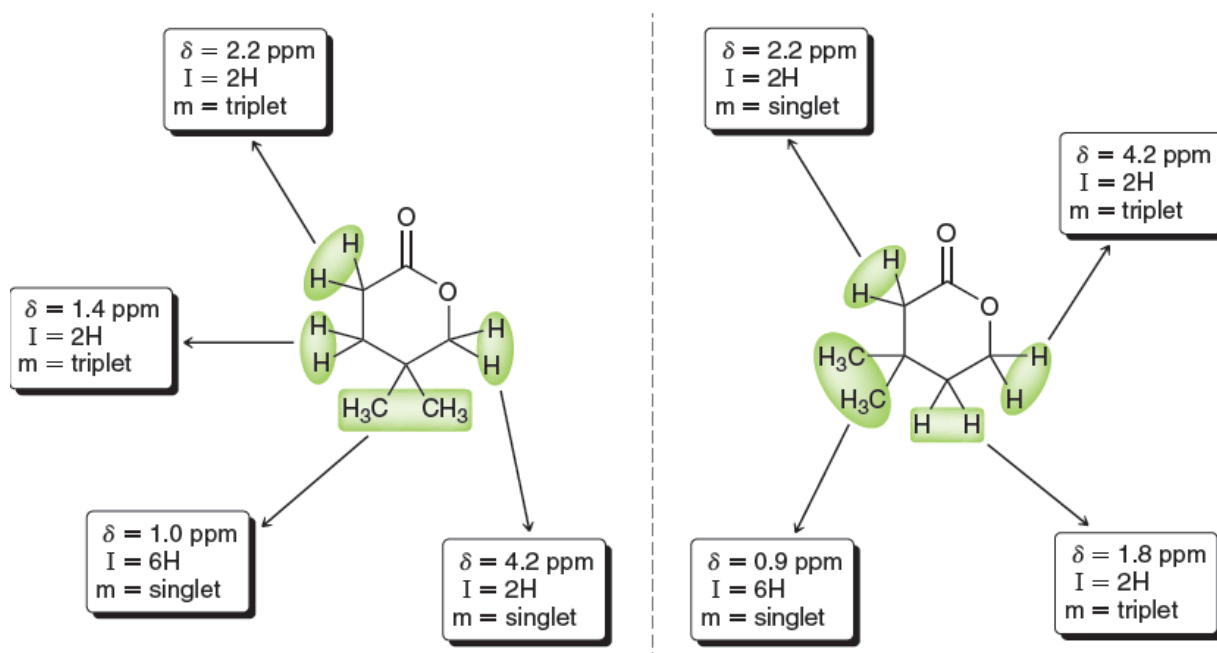


Step 1

Identify the number of signals that each compound will produce.

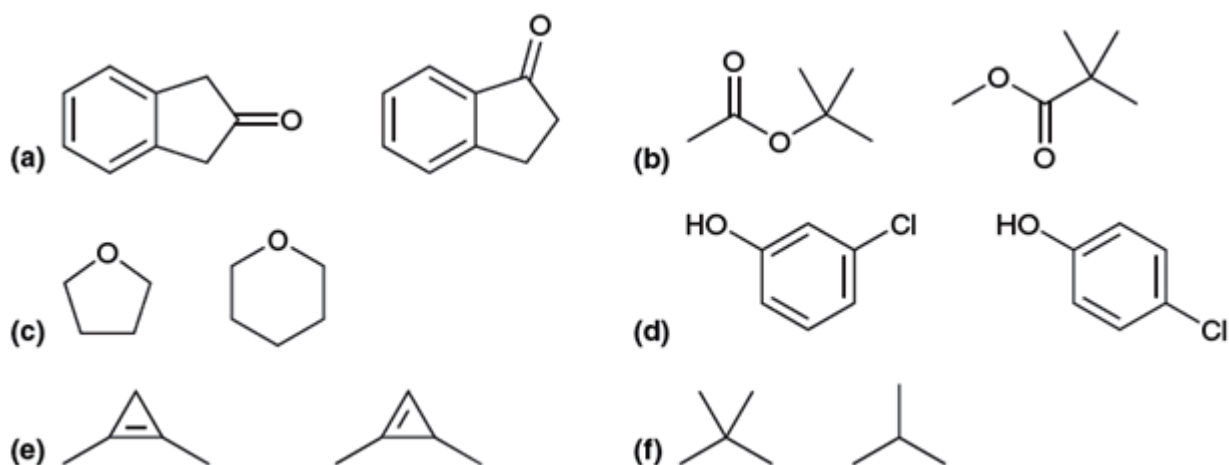


Step 2 Determine the expected chemical shift, integration, and multiplicity of each signal in both compounds.



Step 3 Look for differences in the chemical shifts, multiplicities, or integration values of the signals.

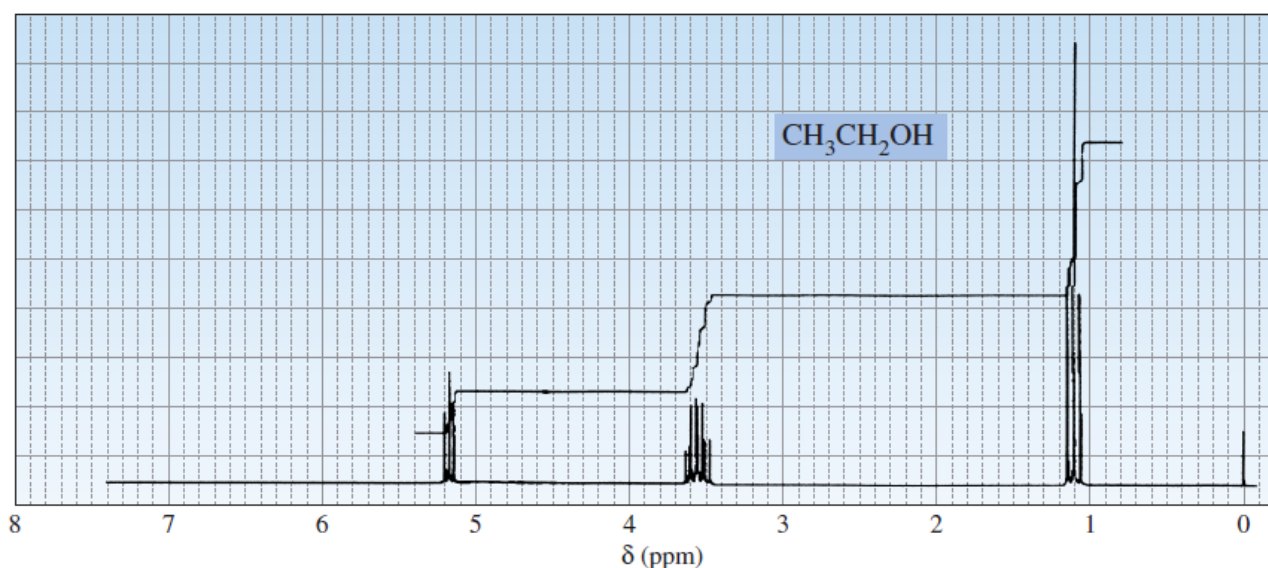
How would you use  $^1\text{H}$  NMR spectroscopy to distinguish between the following compounds?

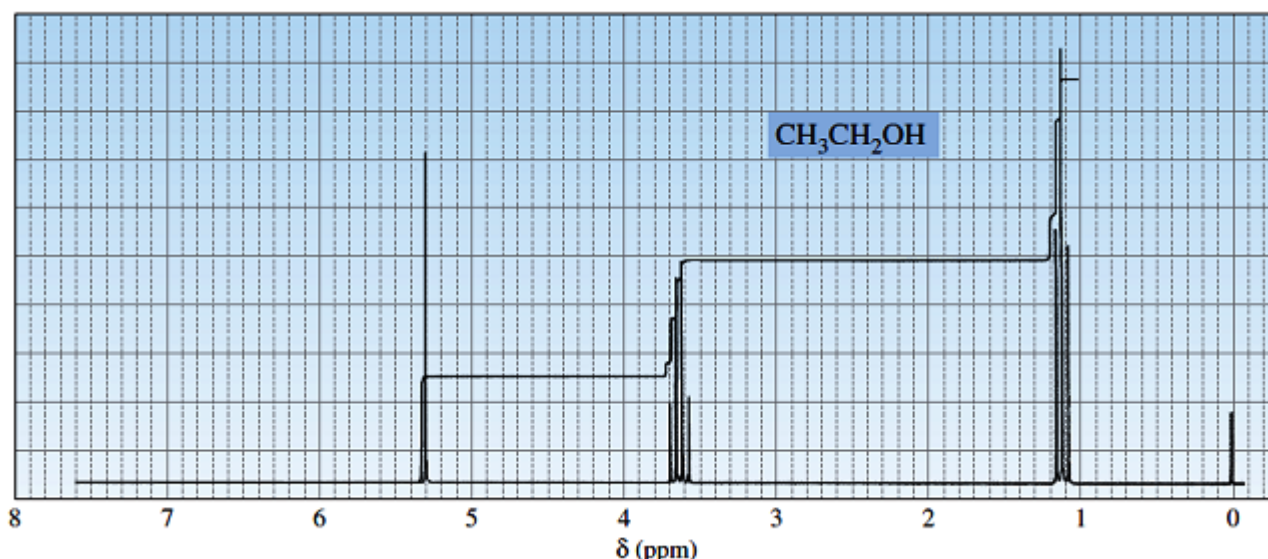


## Protons Bonded to Oxygen and Nitrogen

The chemical shift of a proton bonded to an oxygen or a nitrogen depends on the degree to which the proton is hydrogen bonded—the greater the extent of hydrogen bonding, the greater is the chemical shift—because the extent of hydrogen bonding affects the electron density around the proton. For example, the chemical shift of the OH proton of an alcohol ranges from 2 to 5 ppm; the chemical shift of the OH proton of a carboxylic acid, from 10 to 12 ppm; the chemical shift of the NH proton of an amine, from 1.5 to 4 ppm; and the chemical shift of the NH proton of an amide, from 5 to 8 ppm. The NMR spectrum of pure dry ethanol is shown in Figure 14.28(a), and the NMR spectrum of ethanol with a trace amount of acid is shown in Figure 14.28(b).

a.





The two spectra differ because protons bonded to oxygen undergo proton exchange, which means that they are transferred from one molecule to another. Whether the OH proton and the methylene protons split each other's signals depends on how long a particular proton stays on the OH group

In a sample of pure alcohol, the rate of proton exchange is very slow

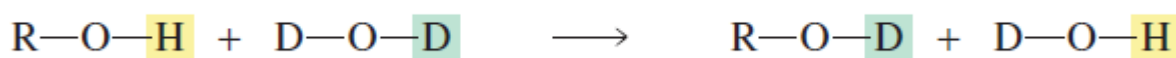
Acids and bases catalyze proton exchange, so if the alcohol is contaminated with just a trace of acid or base, proton exchange becomes rapid.

mechanism for base-catalyzed proton exchange



substituting a deuterium for a hydrogen is a technique used to identify signals and to simplify NMR spectra

after an alcohol's NMR spectrum is obtained, a few drops of are added to the sample and the spectrum is taken again, the OH signal can be identified. It will be the signal that becomes less intense (or disappears) in the second spectrum because of the proton exchange



## Analyzing a $^1\text{H}$ NMR Spectrum

In this section, we will practice analyzing and interpreting NMR spectra, a process that involves four discrete steps:

1. Always begin by inspecting the molecular formula (if it is given), as it provides useful information.

Specifically, calculating the hydrogen deficiency index (HDI) can provide important clues about the structure of the compound. An HDI of zero indicates that the compound does not possess any rings or  $\pi$  bonds. An HDI of 1 indicates that the compound has either one ring or one  $\pi$  bond, an HDI of 4 or more should indicate the possible presence of an aromatic ring:

$$\text{HDI} = \frac{1}{2}(2C + 2 + N - H - X)$$

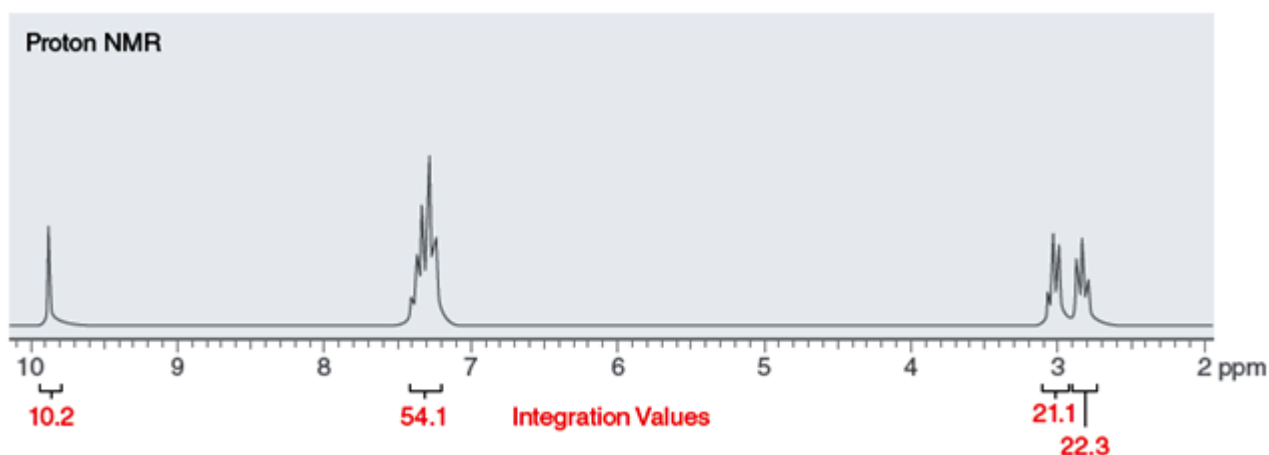
2. Consider the number of signals and integration of each signal (gives clues about the symmetry of the compound).

3. Analyze each signal (chemical shift, integration, and multiplicity) and then draw fragments consistent with each signal. These fragments become our puzzle pieces that must be assembled to produce a molecular structure.

4. Assemble the fragments into a molecular structure.

The following exercise illustrates how this is done.

Identify the structure of a compound with molecular formula  $\text{C}_9\text{H}_{10}\text{O}$  that exhibits the following  $^1\text{H}$  NMR spectrum:



Solution

Begin by calculating the HDI. The molecular formula indicates 9 carbon atoms, which would require 20 hydrogen atoms in order to be fully saturated. There are only 10 hydrogen atoms, which means that 10 hydrogen atoms are missing, and therefore, the HDI is 5. This is a large number, and it would not be efficient to think about all the possible ways to have five degrees of unsaturation. However, anytime we encounter an HDI of 4 or more, we should be on the lookout for an aromatic ring. We must keep this in mind when analyzing the spectrum.

We should expect to see an aromatic ring (HDI = 4) plus one other degree of unsaturation (either a ring or a double bond).

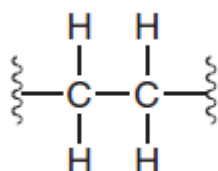
Next, consider the number of signals and the integration value for each signal. Be on the lookout for integration values that would suggest the presence of symmetry elements.

For example, a signal with an integration of 4 would suggest two equivalent CH<sub>2</sub> groups.

In this spectrum, we see four signals. In order to analyze the integration of each signal, we must first divide by the lowest number (10.2):

$$\frac{10.2}{10.2} = 1 \qquad \frac{54.1}{10.2} = 5.30 \qquad \frac{21.1}{10.2} = 2.07 \qquad \frac{22.3}{10.2} = 2.19$$

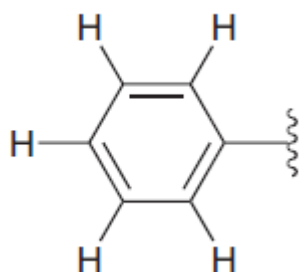
The ratio is approximately 1 : 5 : 2 : 2. Now look at the molecular formula. There are 10 protons in the compound, so the relative integration values represent the actual number of protons giving rise to each signal. Now analyze each signal. Starting upfield, there are two triplets, each with an integration of 2. This suggests that there are two adjacent methylene groups.



These signals do not appear at 1.2, where methylene groups are expected, so one or more factors are shifting these signals downfield. Our proposed structure must take this into account.

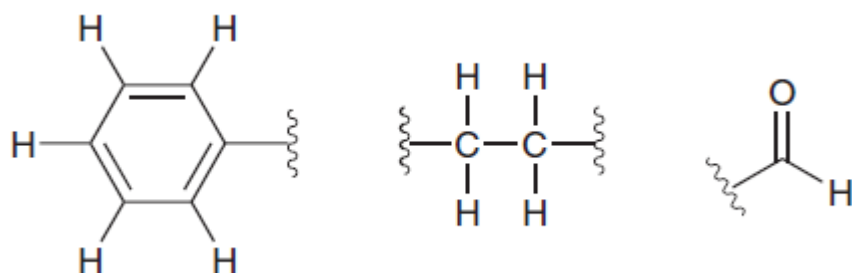
Moving downfield through the spectrum, the next signal appears just above 7 ppm, characteristic of aromatic protons (just as we suspected after analyzing the HDI). The multiplicity of aromatic protons only rarely gives useful information. More often, a multiplet of overlapping signals is observed. But the integration value gives valuable information.

Specifically, there are five aromatic protons, which means that the aromatic ring is monosubstituted.

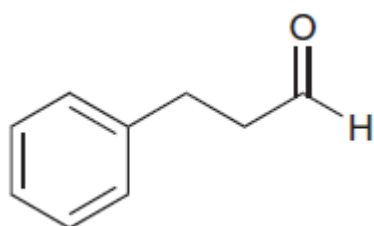


Five aromatic protons

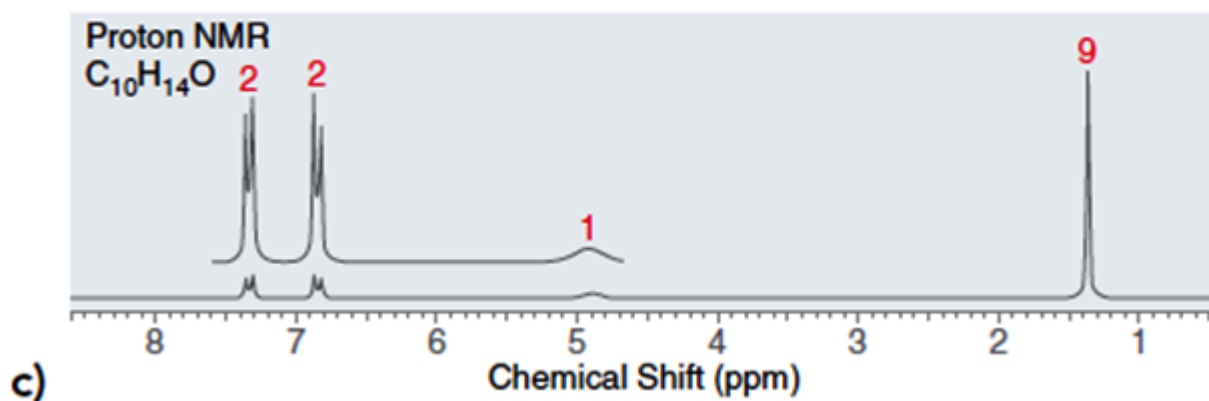
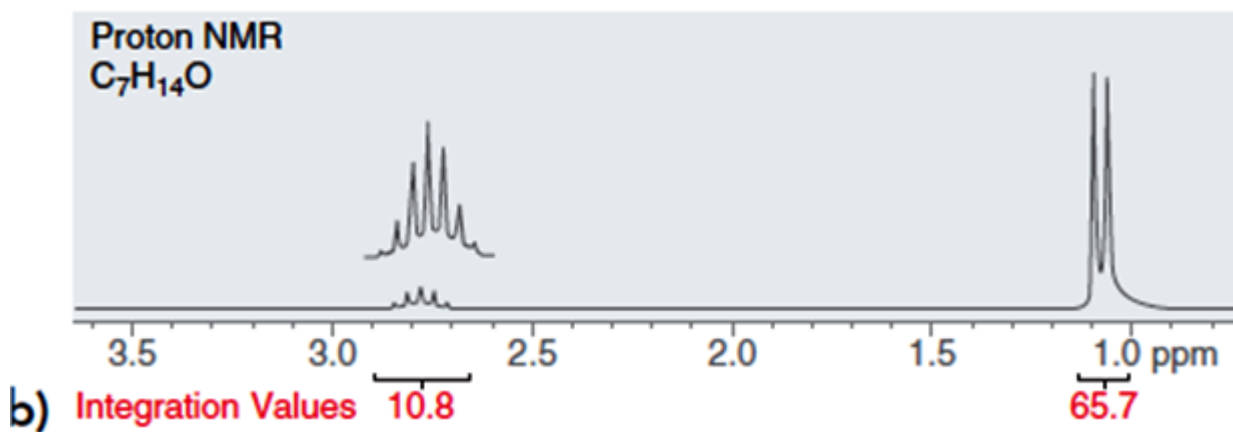
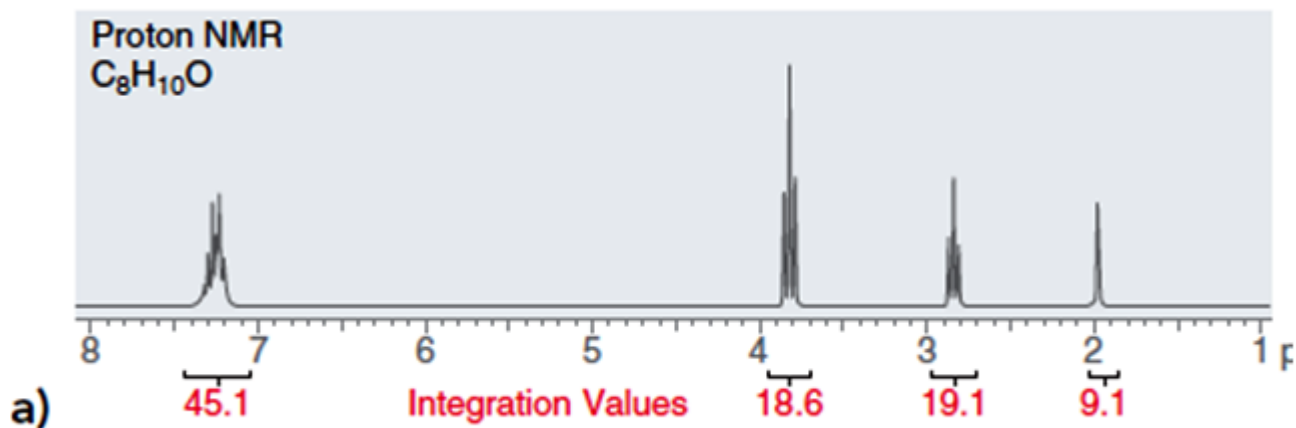
Next, move on to the last signal, which is a singlet at 10 ppm with an integration 1. This is suggestive of an aldehydic proton. Our analysis has produced the following fragments:



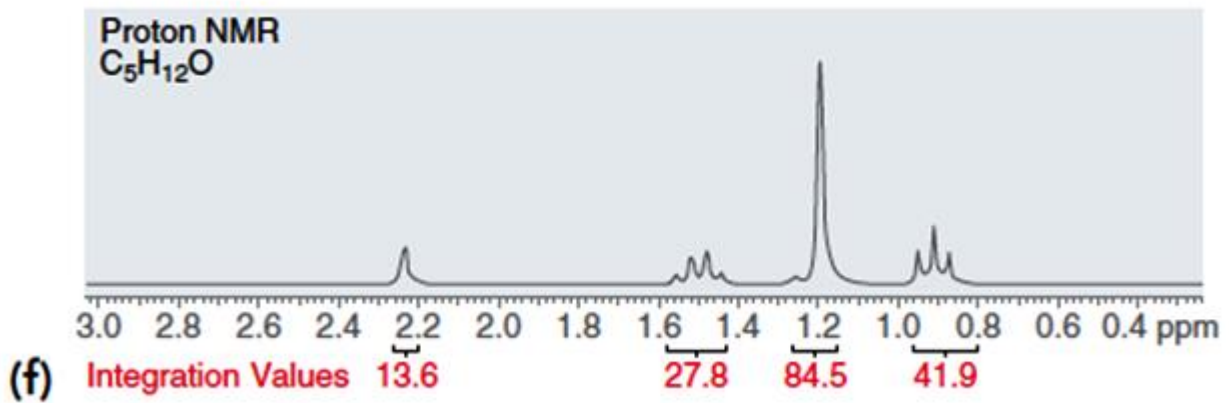
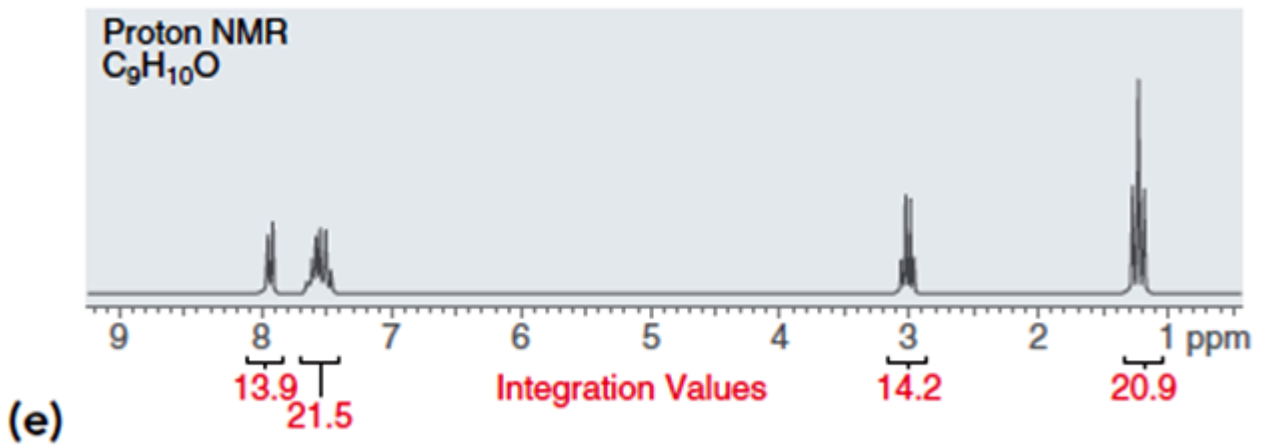
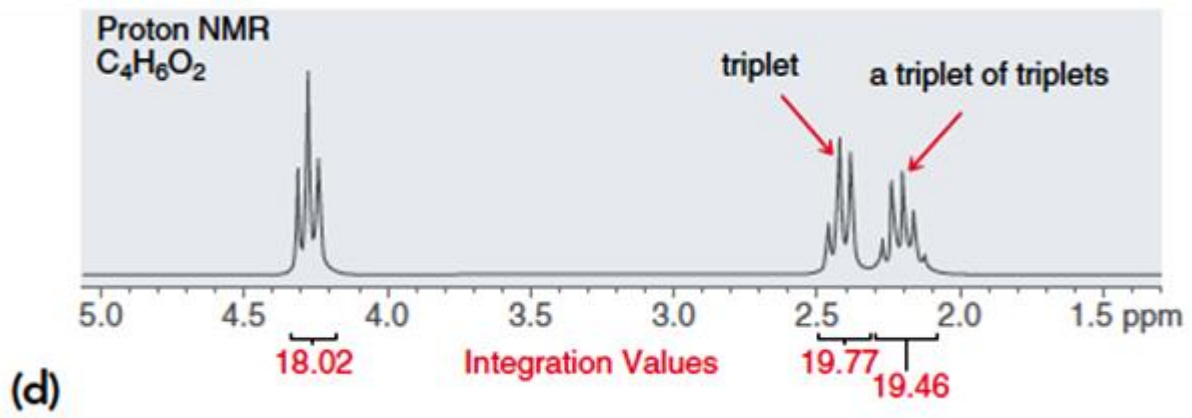
The final step is to assemble these fragments. Fortunately, there is only one way to assemble these three puzzle pieces.



Propose a structure that is consistent with each of the following  $^1\text{H}$  NMR spectra. In each case, the molecular formula is provided







$^{13}C$  NMR Spectroscopy

Many of the principles that apply to  $^1\text{H}$  NMR spectroscopy also apply to  $^{13}\text{C}$  NMR spectroscopy, but there are a few major differences

The number of signals in a  $^{13}\text{C}$  NMR spectrum tells you how many different kinds of carbons as the number of signals in an  $^1\text{H}$  NMR spectrum.

The principles behind HNMR and  $^{13}\text{C}$  NMR spectroscopy are essentially the same.

There are some differences:

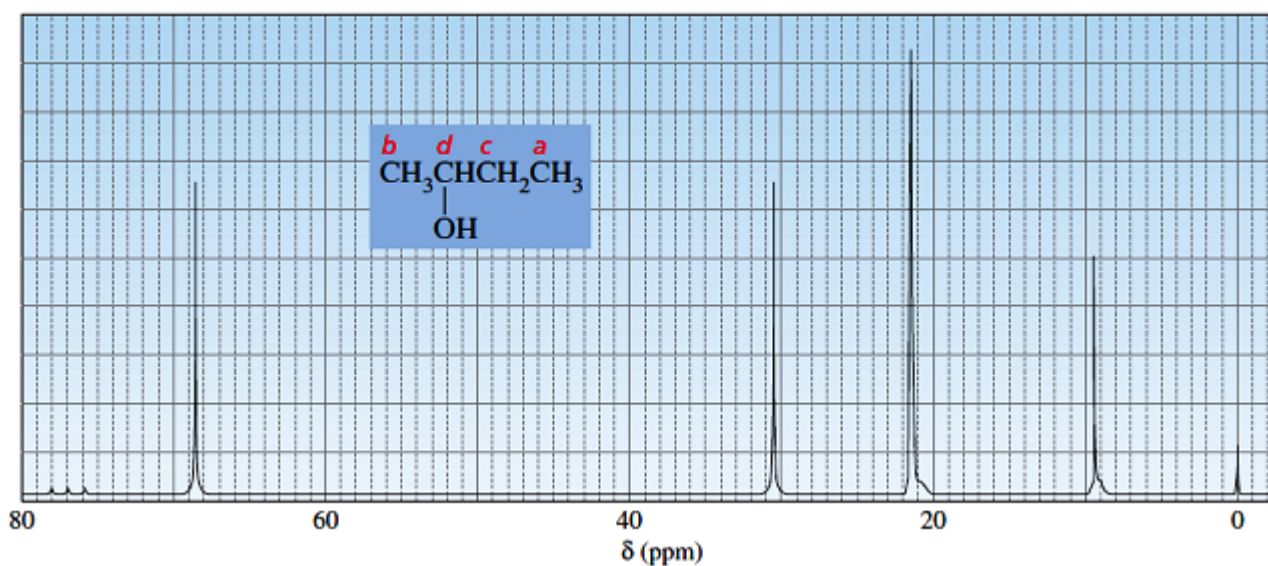
- $^{13}\text{C}$  NMR requires Fourier transform techniques Without Fourier transform, it could take days to record the number of scans required for a NMR spectrum.
- The individual signals are weak because the isotope of carbon that gives rise to NMR signals constitutes only 1.11% of carbon atoms.

The low abundance of means that the intensities of the signals in  $^{13}\text{C}$  NMR compared with those in  $^1\text{H}$  NMR are reduced by a factor of approximately 100.

In addition, the gyromagnetic ratio ( $\gamma$ ) of is about one-fourth that of and the intensity of a signal is proportional to  $\gamma^3$  Therefore, the overall intensity of a signal is about 6400 times ( $100 * 4 * 4 * 4$ ) less than the intensity of an signal.

- In  $^1\text{H}$  NMR spectroscopy, we saw that each signal has three characteristics (chemical shift, integration, and multiplicity). In  $^{13}\text{C}$  NMR spectroscopy, only the chemical shift is generally reported.
- The integration and multiplicity of  $^{13}\text{C}$  signals are not reported
- The reference compound used in  $^{13}\text{C}$  NMR is TMS.

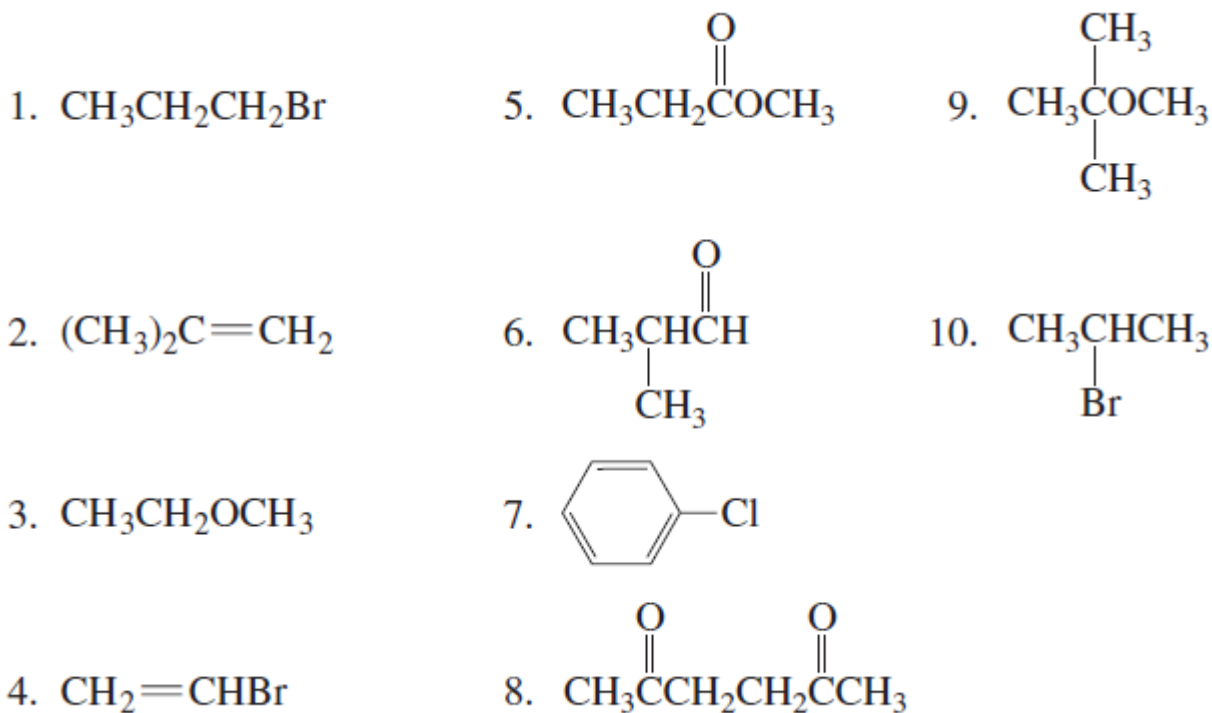
The NMR spectrum of 2-butanol 2-Butanol has carbons in four different environments, so there are four signals in the spectrum.



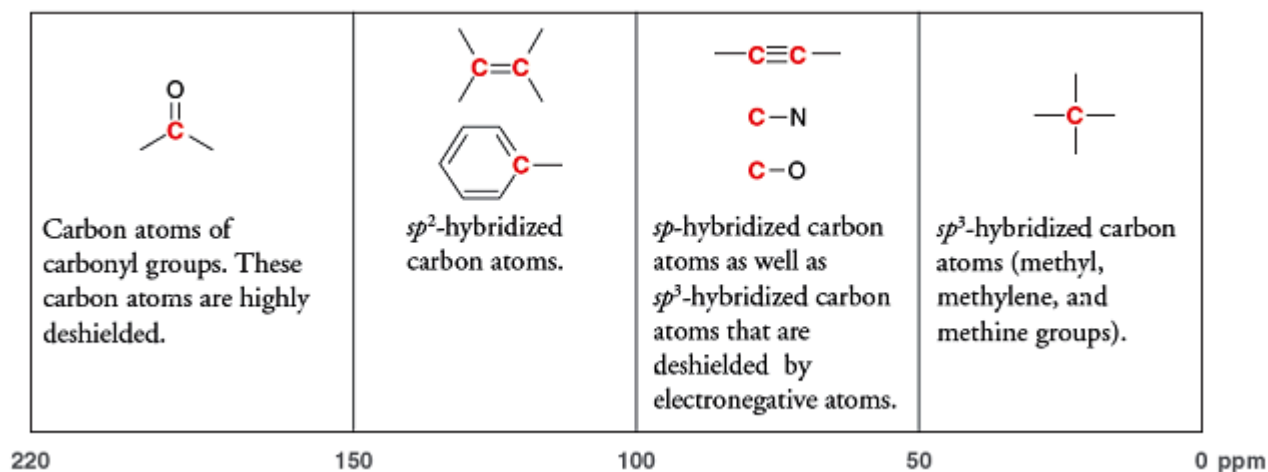
The relative positions of the signals depend on the same factors that determine the relative positions of the proton signals in NMR. Carbons in electron-dense environments produce low-frequency signals, and carbons close to electron-withdrawing groups produce high-frequency signals.

Answer the following questions for each of the compounds:

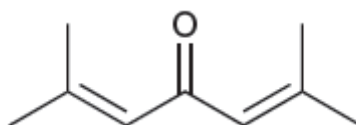
- a. How many signals are in the NMR spectrum?
- b. Which signal is at the lowest frequency?



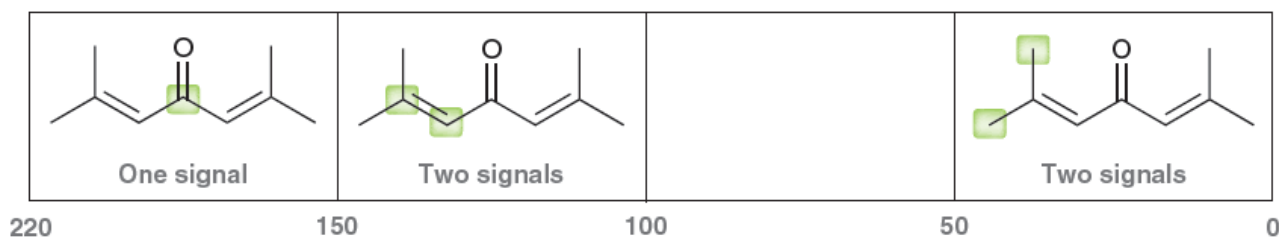
The location of each signal is dependent on shielding and deshielding effects, just as we saw in  $^1\text{H}$  NMR spectroscopy. Figure shows the chemical shifts of several important types of carbon atoms.



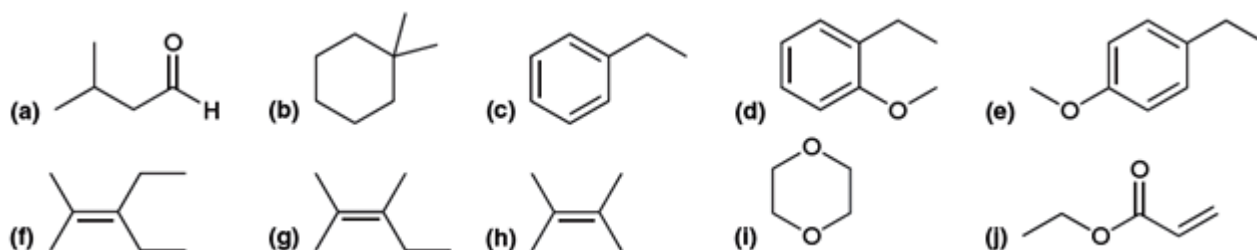
Predict the number of signals and the location of each signal in a  $^{13}\text{C}$  NMR spectrum of this compound.



Solution

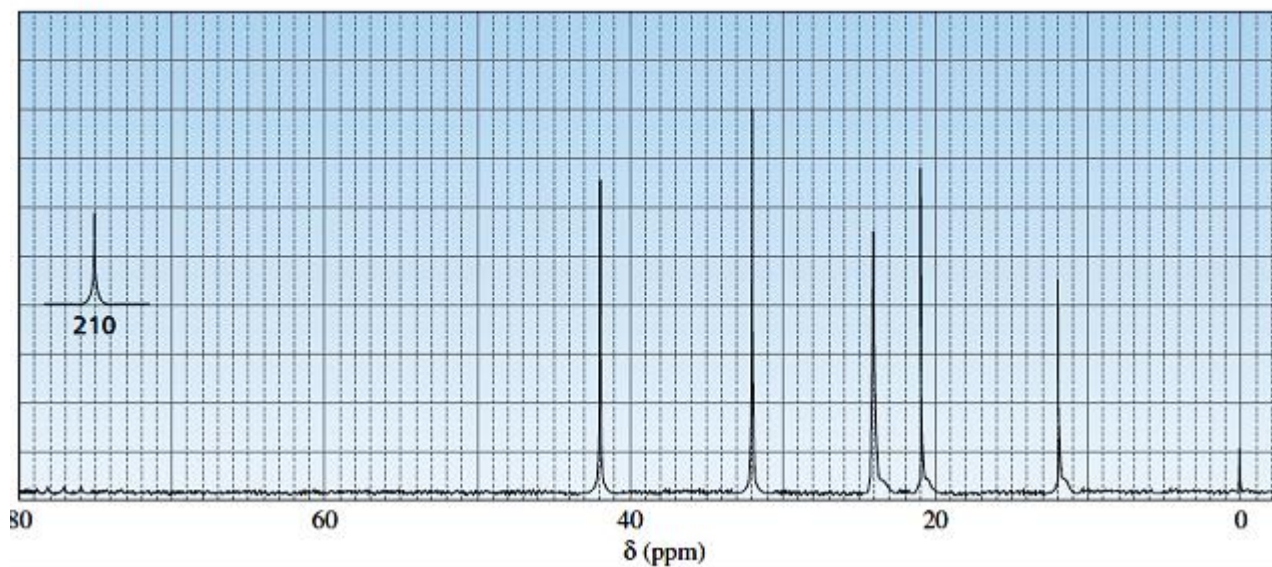


For each of the following compounds, predict the number of signals and location of each signal in a  $^{13}\text{C}$  NMR spectrum:

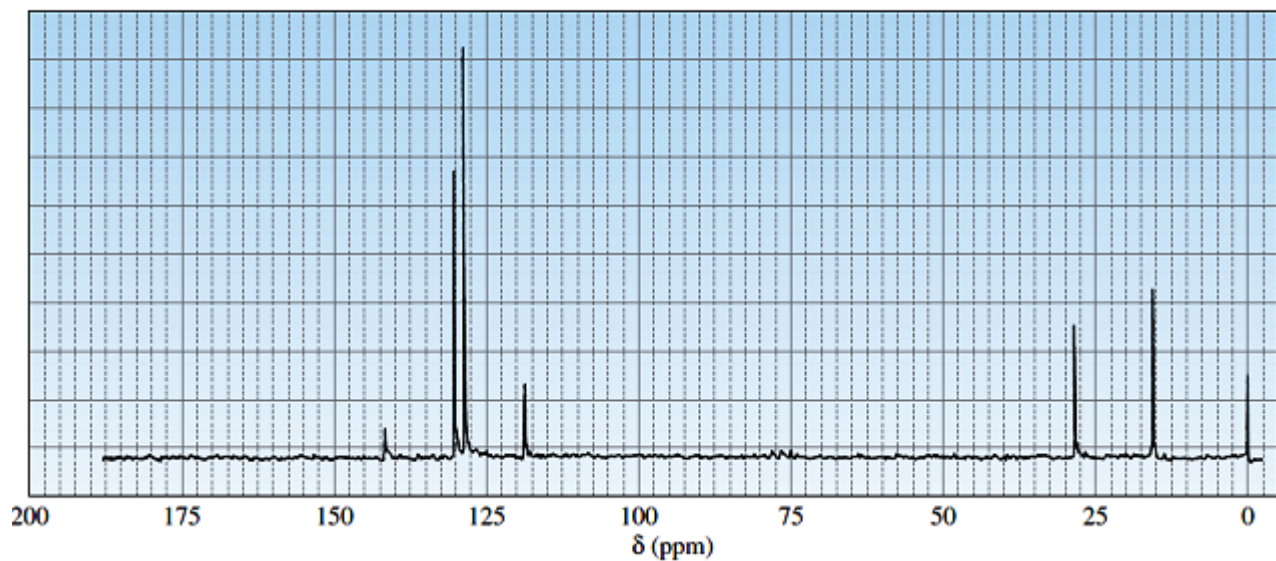


Identify each compound in the following Figure from its molecular formula and its NMR Spectrum

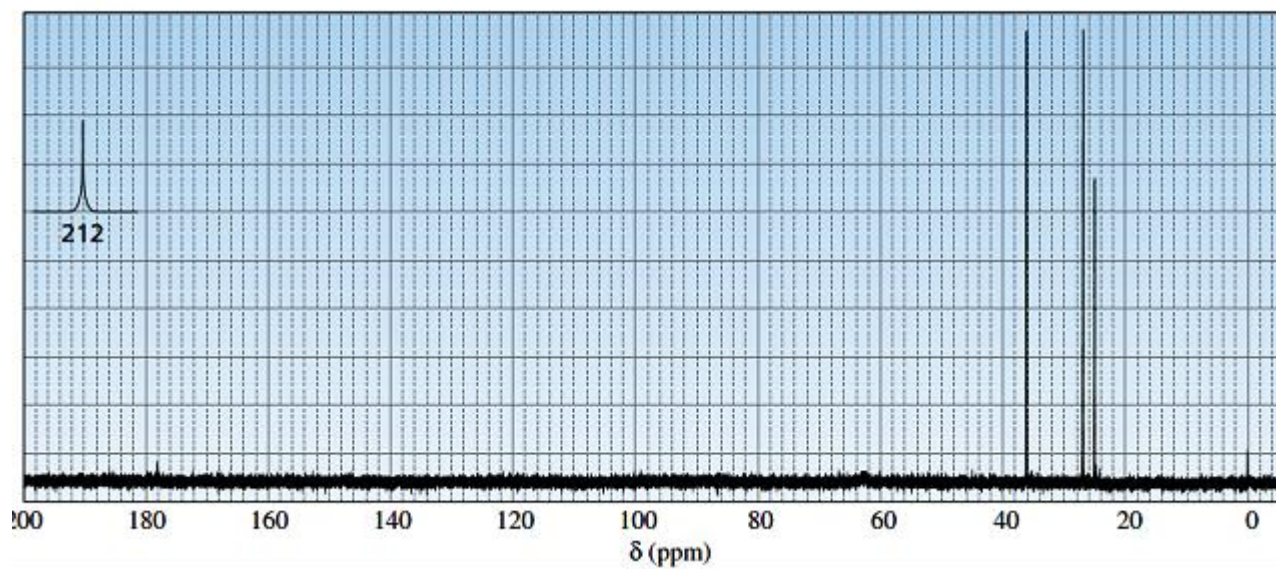
a.  $\text{C}_{11}\text{H}_{22}\text{O}$



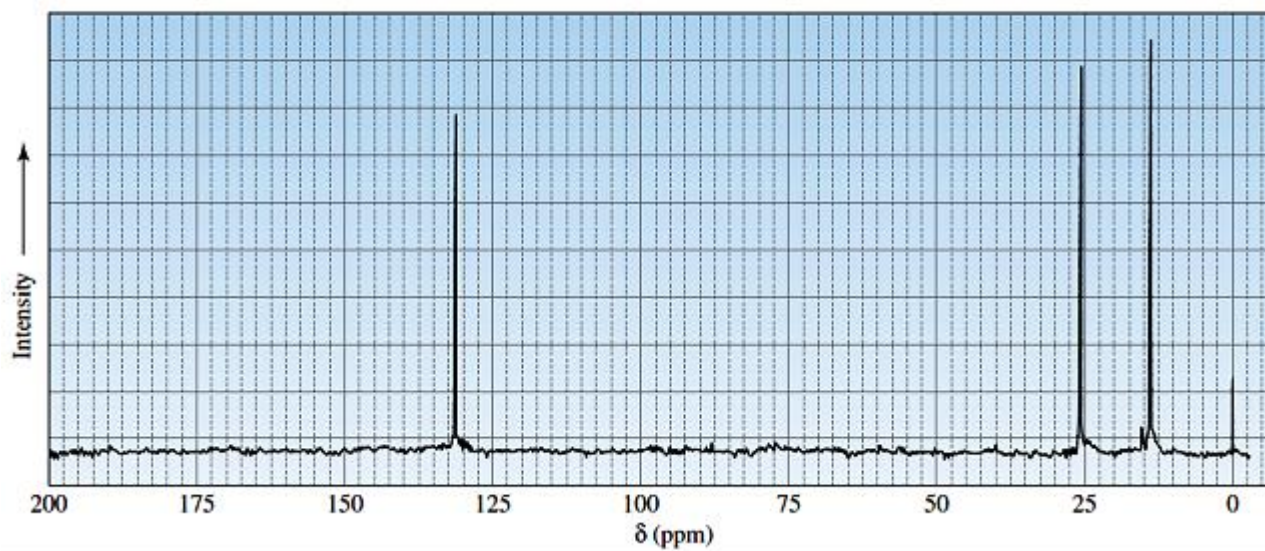
b.  $C_8H_9Br$



c.  $C_6H_{10}O$



d.  $C_6H_{12}$











## DEPT $^{13}\text{C}$ NMR Spectroscopy

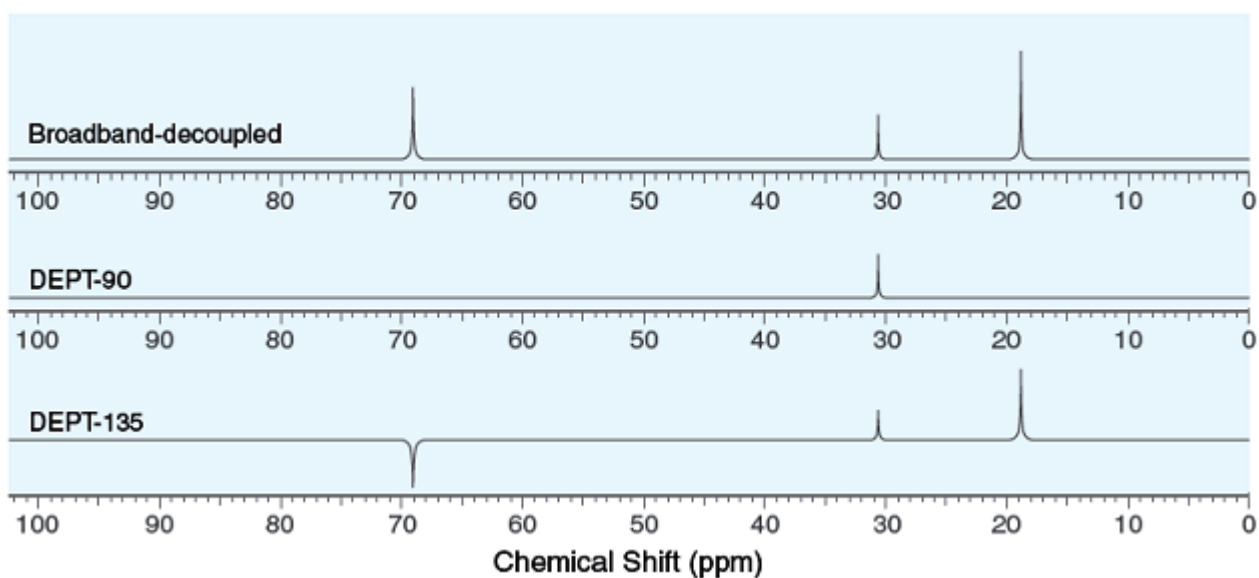
A technique called DEPT NMR has been developed to distinguish among  $\text{CH}_3$ ,  $\text{CH}_2$  and  $\text{CH}$  groups. (DEPT stands for distortionless enhancement by polarization transfer.)

This technique involves the acquisition of several spectra. First, a regular broadband-decoupled  $^{13}\text{C}$  spectrum is acquired, indicating the chemical shifts associated with all carbon atoms in the compound. Then a special pulse sequence is utilized to produce a spectrum called a DEPT-90, in which only signals from  $\text{CH}$  groups appear. This spectrum does not show any signals resulting from  $\text{CH}_3$  groups,  $\text{CH}_2$  groups, or quaternary carbon atoms ( $\text{C}$  with no protons). Then, a different pulse sequence is employed to generate a spectrum, called a DEPT-135, in which  $\text{CH}_3$  groups and  $\text{CH}$  groups appear as positive signals,  $\text{CH}_2$  groups appear as negative signals (pointing down), and quaternary carbon atoms do not appear.

By comparing all of the spectra, it is possible to identify each signal in the broadband-decoupled spectrum as arising from either a  $\text{CH}_3$  group, a  $\text{CH}_2$  group, a  $\text{CH}$  group, or a quaternary carbon atom. This information is summarized in Table 4.

|                     | $\text{CH}_3$   | $\text{CH}_2$   | $\text{CH}$   | $\text{C}$  |
|---------------------|---|---|---|---|
| BROADBAND DECOUPLED |  |  |  |  |
| DEPT-90             | —   | —   |  | —   |
| DEPT-135            |  |  |  | —   |

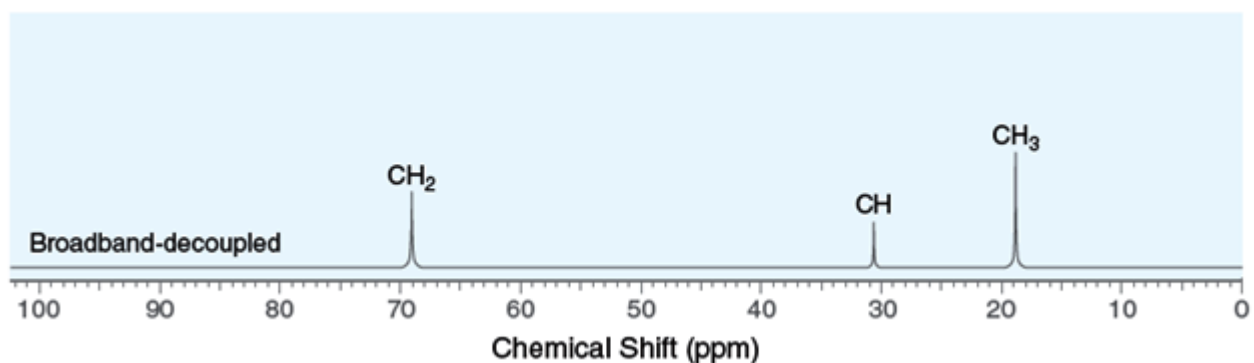
Determine the structure of an alcohol with molecular formula  $\text{C}_4\text{H}_{10}\text{O}$  that exhibits the following  $^{13}\text{C}$  NMR spectra:



The signal at approximately 69 ppm is a  $\text{CH}_2$  group (signal is negative in DEPT-135).

- The signal at approximately 30 ppm is a  $\text{CH}$  group (signal is positive in all spectra).
- The signal at approximately 19 ppm is a  $\text{CH}_3$  group (signal is positive in the broadband-decoupled spectrum, absent in DEPT-90, and positive in DEPT-135).

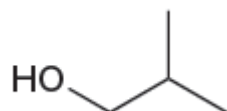
We can now record this information on the broadband-decoupled spectrum to aid in our analysis.



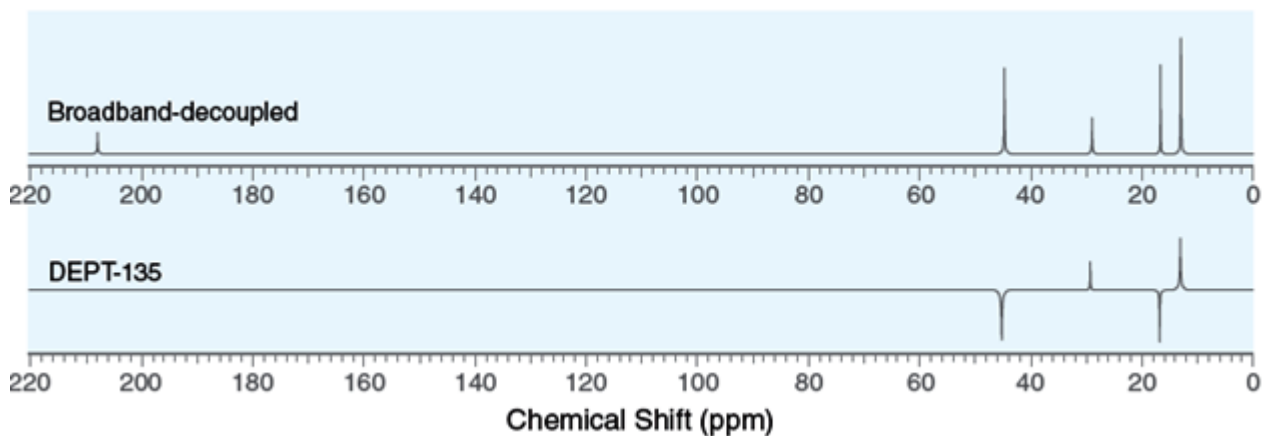
In order to determine which signal represents two carbon atoms, we notice that the molecular formula indicates that the structure must have 10 protons. So far, we have only accounted for 7 of the protons ( $\text{CH}_2 + \text{CH} + \text{CH}_3 + \text{OH} = 7$  protons). We need to account for 3 more protons.

Therefore, we can conclude that the  $\text{CH}_3$  signal must represent 2 equivalent carbon atoms.





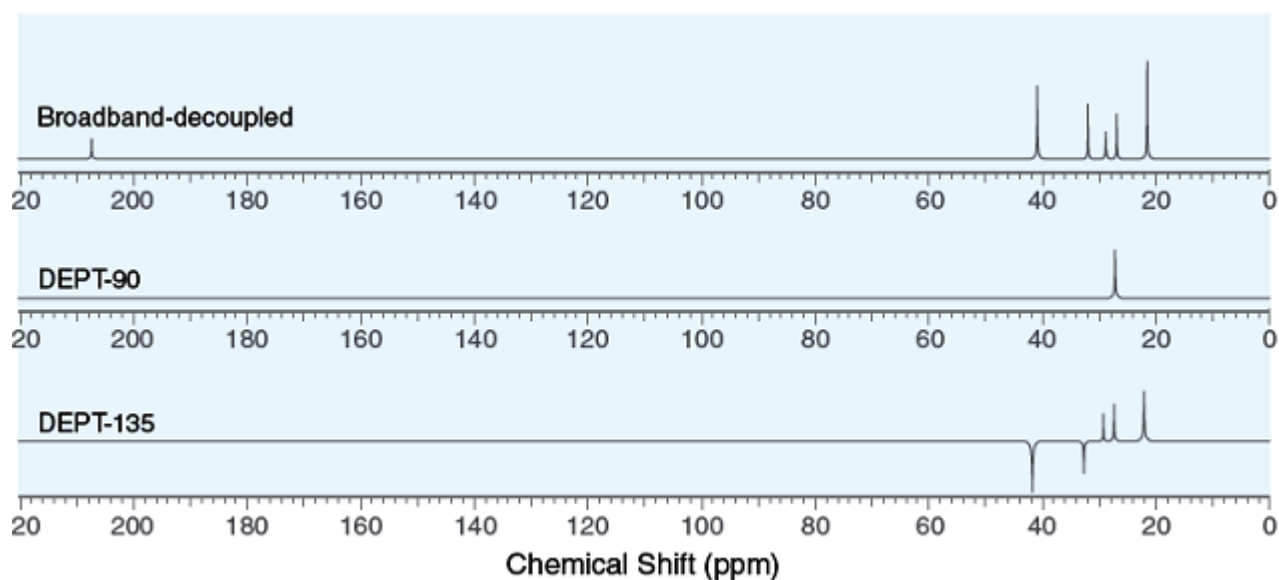
Determine the structure of a compound with molecular formula  $C_5H_{10}O$  that exhibits the following broadband-decoupled and DEPT-135 spectra. The DEPT-90 spectrum has no signals.



Determine the structure of an alcohol with molecular formula  $C_5H_{12}O$  that exhibits the following signals in its  $^{13}C$  NMR spectra:

- (a) Broadband decoupled:  $73.8 \delta$ ,  $29.1 \delta$ , and  $9.5 \delta$
- (b) DEPT-90:  $73.8 \delta$
- (c) DEPT-135: positive signals at  $73.8 \delta$  and  $9.5 \delta$ ; negative signal at  $29.1 \delta$

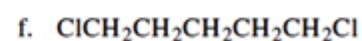
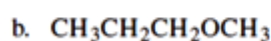
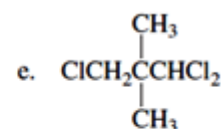
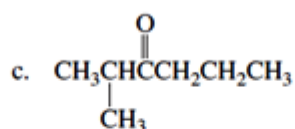
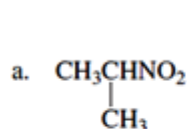
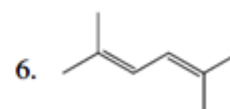
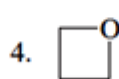
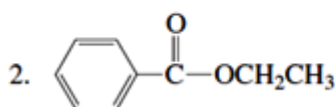
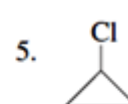
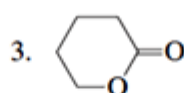
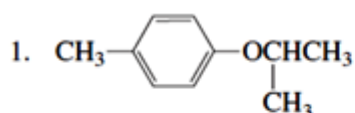
A compound with molecular formula  $C_7H_{14}O$  exhibits the following  $^{13}C$  NMR spectra



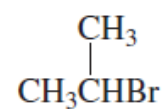
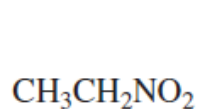
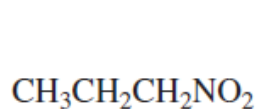
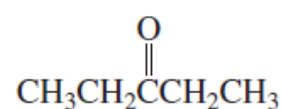
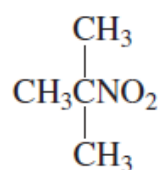
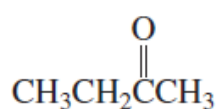
How many signals are produced by each of the following compounds in its

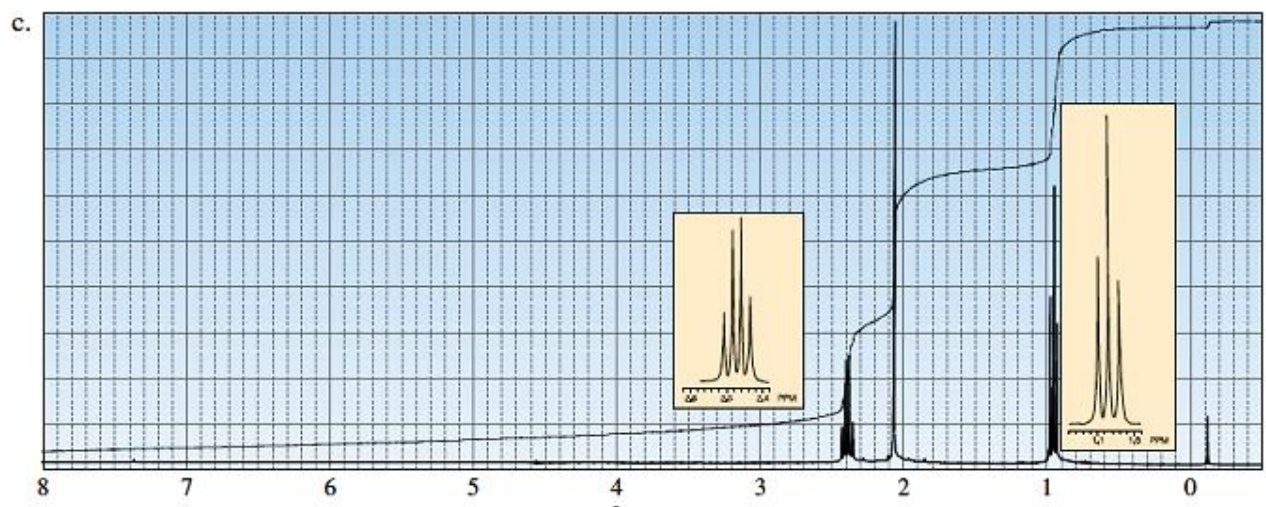
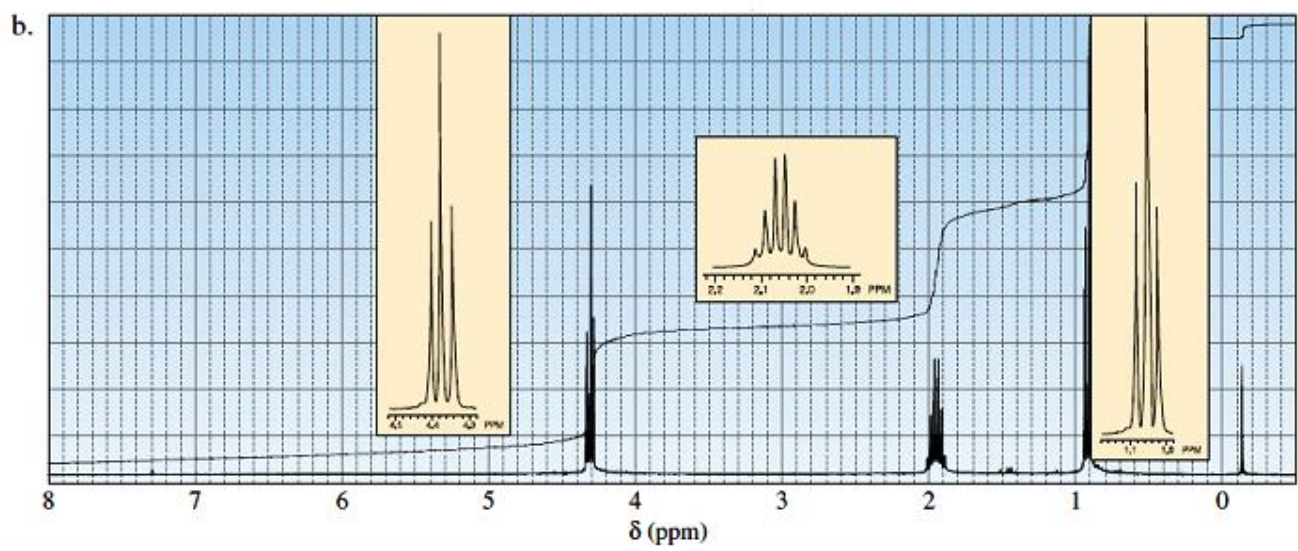
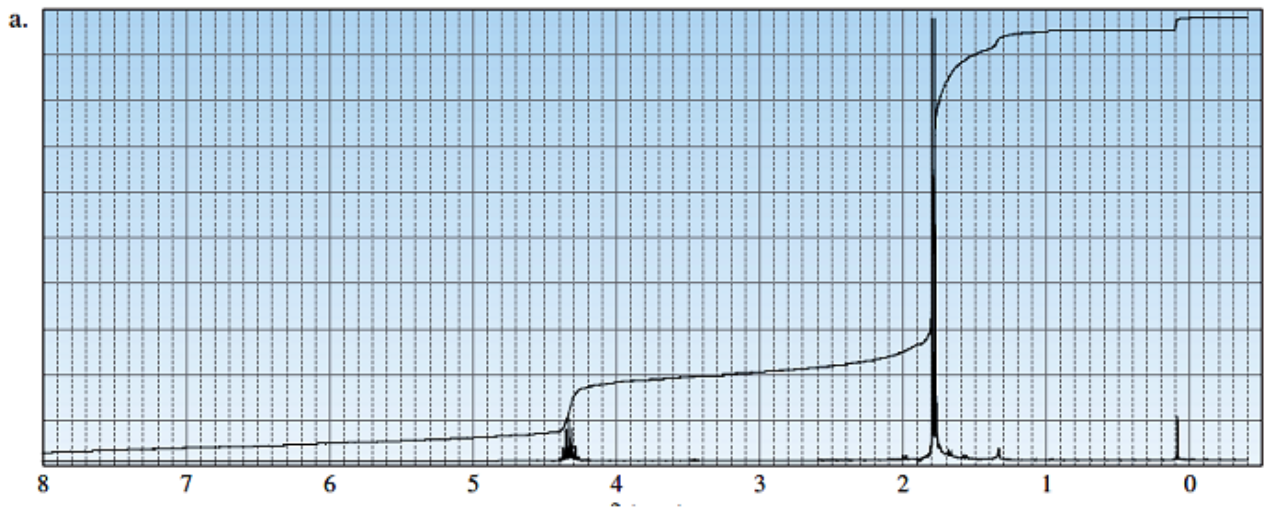
a. <sup>1</sup>H NMR spectrum?

b. <sup>13</sup>C NMR spectrum?

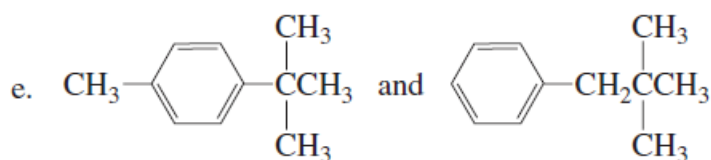
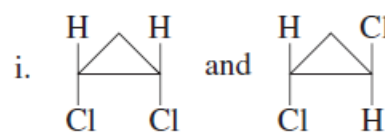
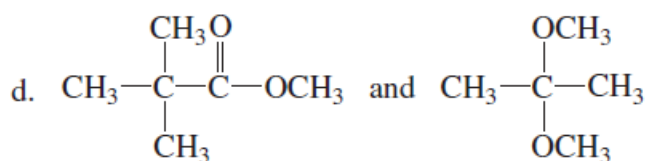
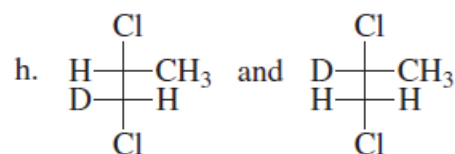
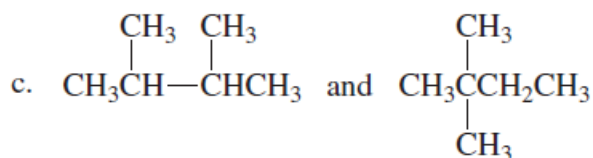
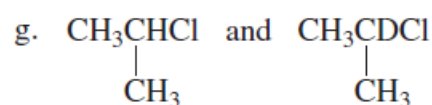
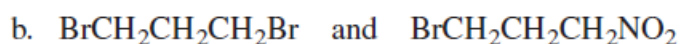
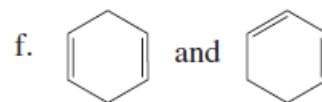
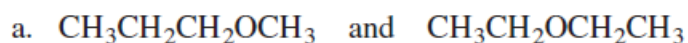


Match each of the <sup>1</sup>H NMR spectra on page 57  h one of the following compounds:

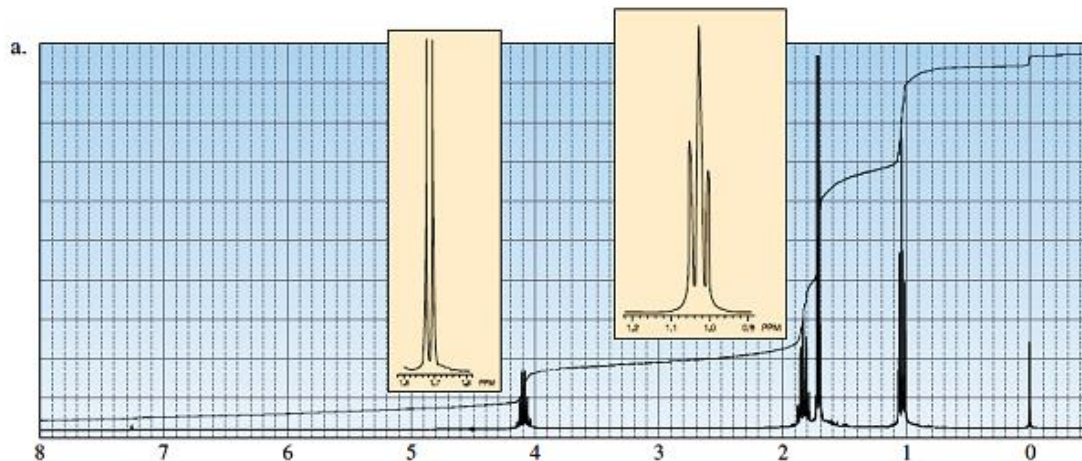


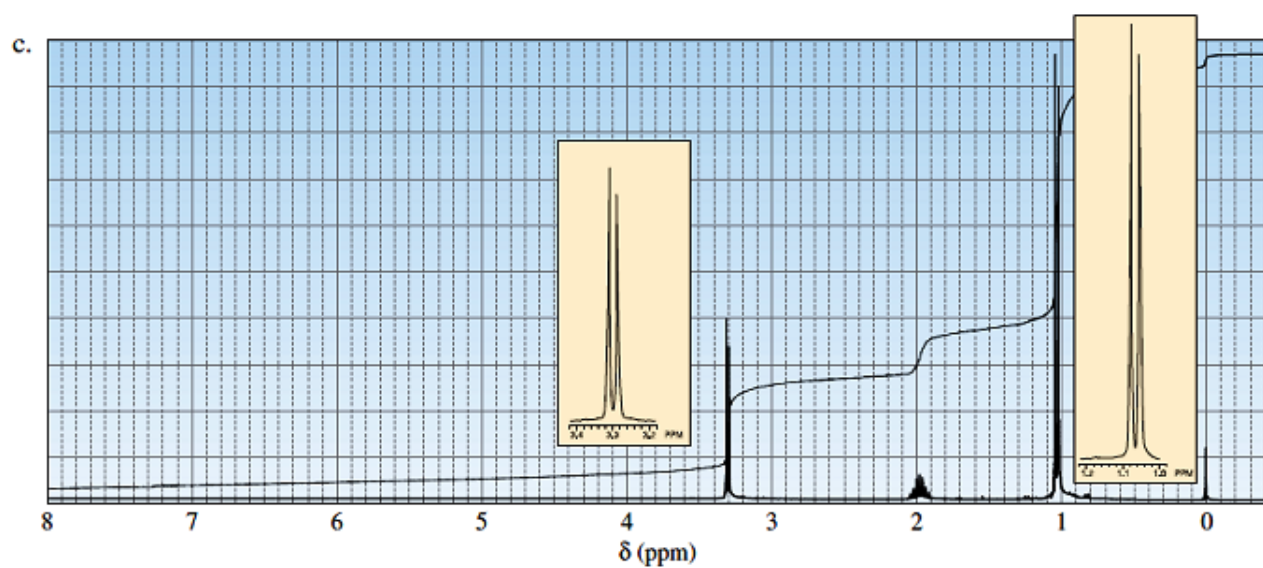
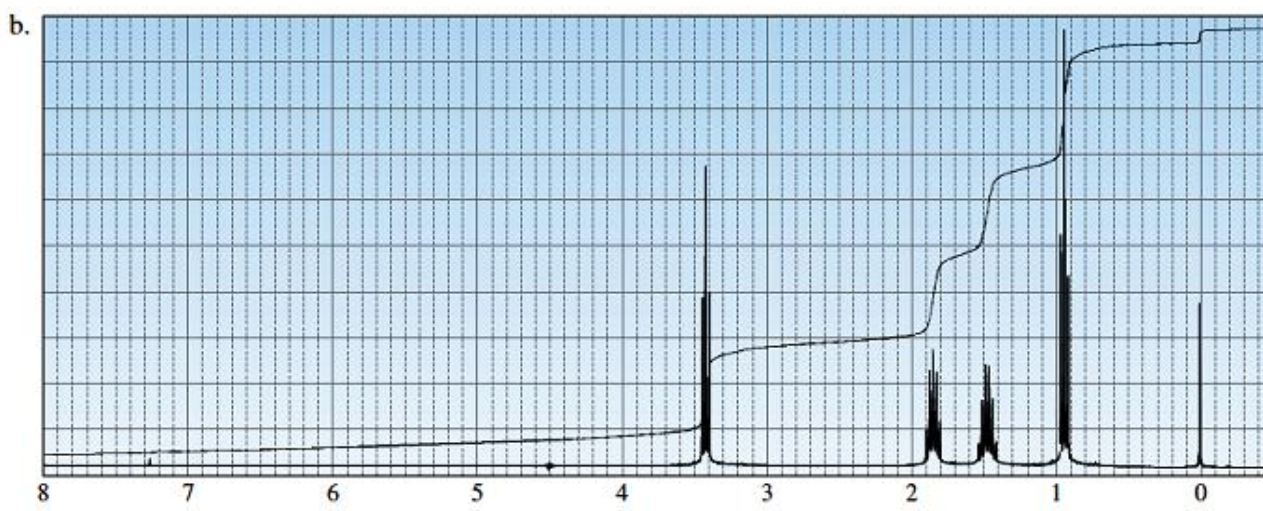


How could  $^1\text{H}$  NMR distinguish between the compounds in each of the following pairs?



The  $^1\text{H}$  NMR spectra of three isomers with molecular formula  $\text{C}_4\text{H}_9\text{Br}$  are shown here. Which isomer produces which spectrum





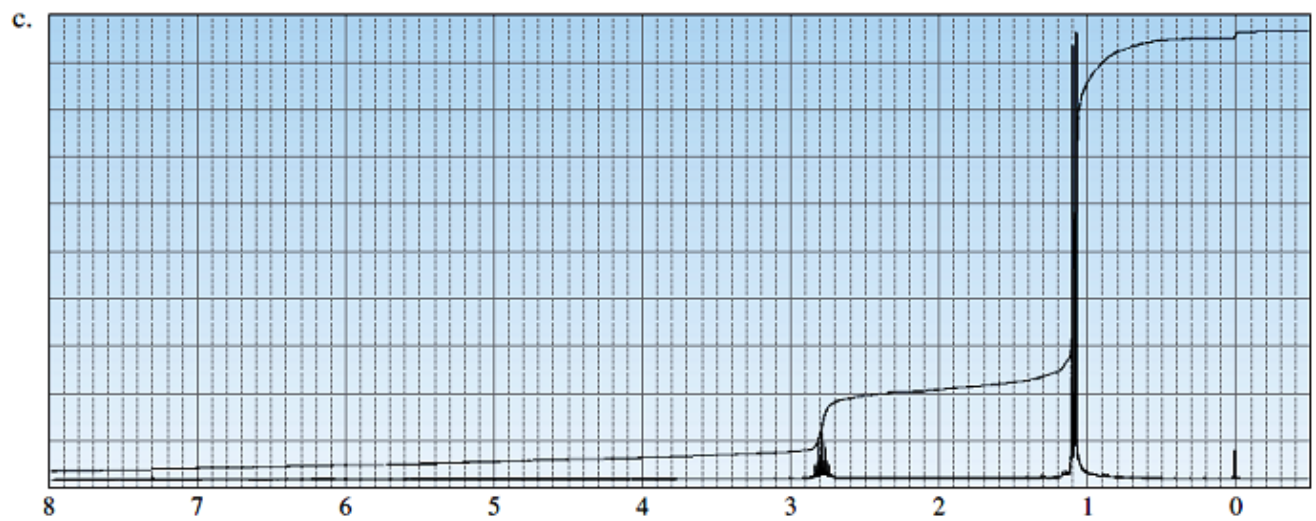
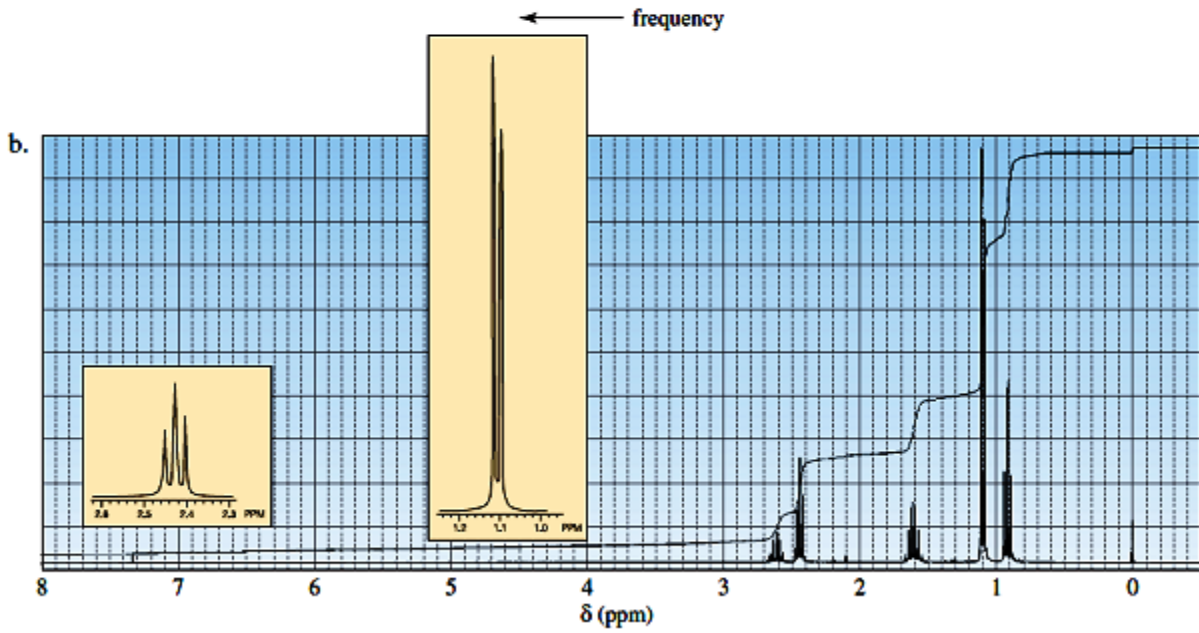
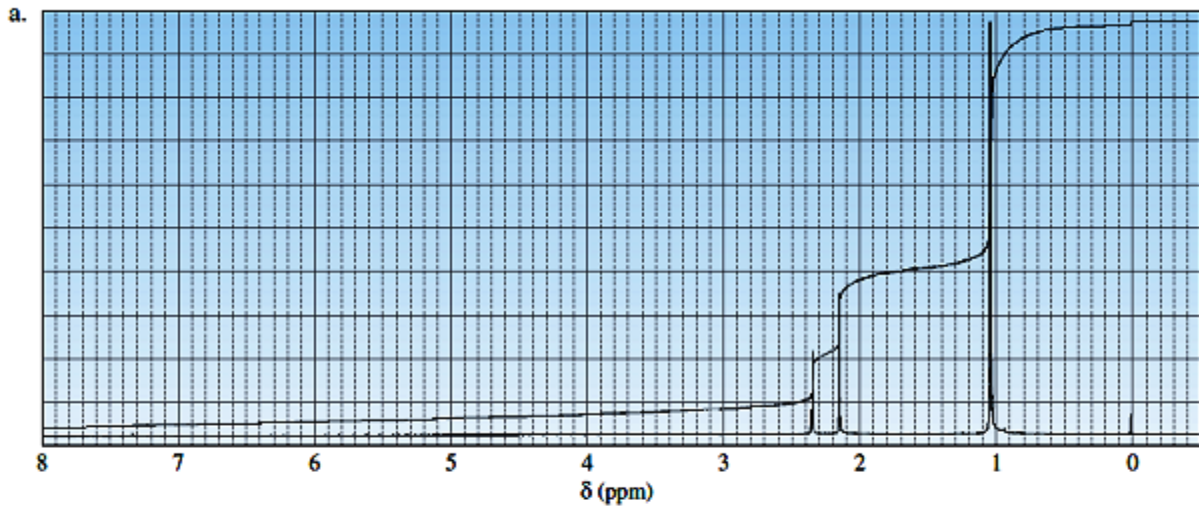
Identify each of the following compounds from the  $^1\text{H}$  NMR data and molecular formula. The number of hydrogens responsible for each signal is shown in parentheses.

a.  $\text{C}_4\text{H}_8\text{Br}_2$  1.97 ppm (6) singlet  
3.89 ppm (2) singlet

b.  $\text{C}_8\text{H}_9\text{Br}$  2.01 ppm (3) doublet  
5.14 ppm (1) quartet  
7.35 ppm (5) broad singlet

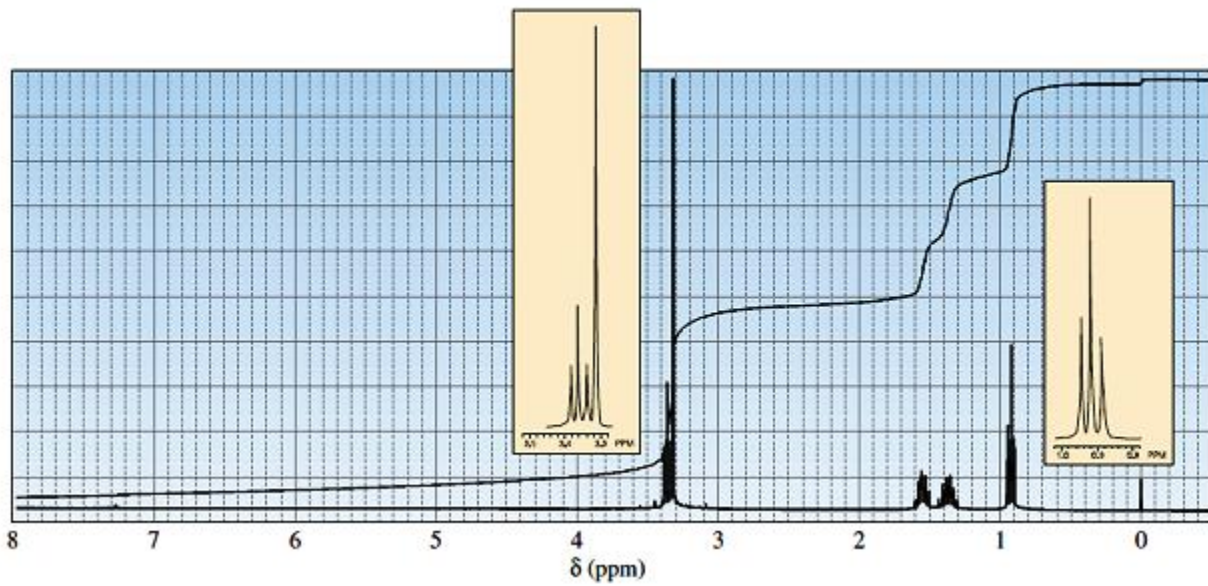
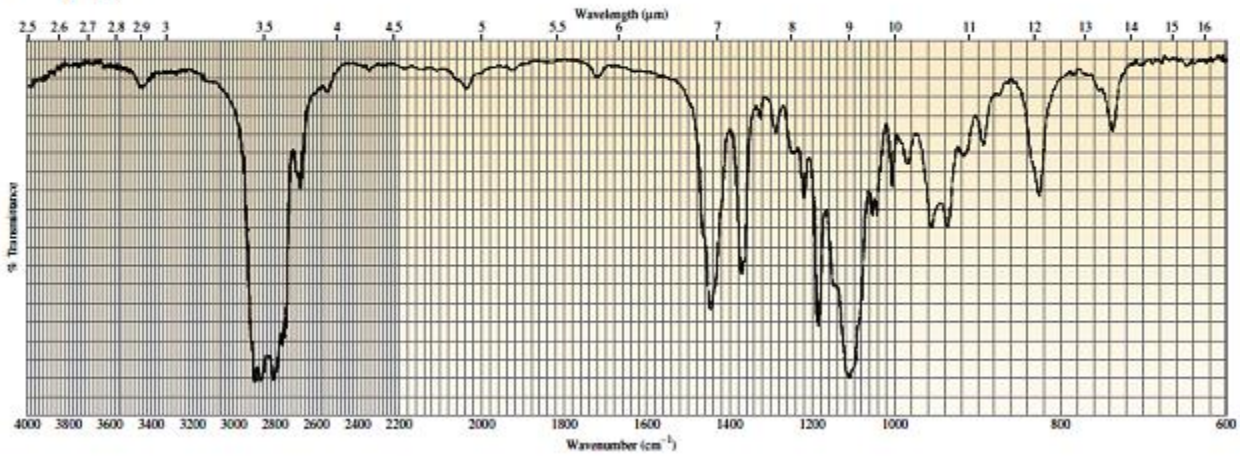
c.  $\text{C}_5\text{H}_{10}\text{O}_2$  1.15 ppm (3) triplet  
1.25 ppm (3) triplet  
2.33 ppm (2) quartet  
4.13 ppm (2) quartet

The  $^1\text{H}$  NMR spectra of three isomers with molecular formula  $\text{C}_7\text{H}_{14}\text{O}$  are shown here. Which isomer produces

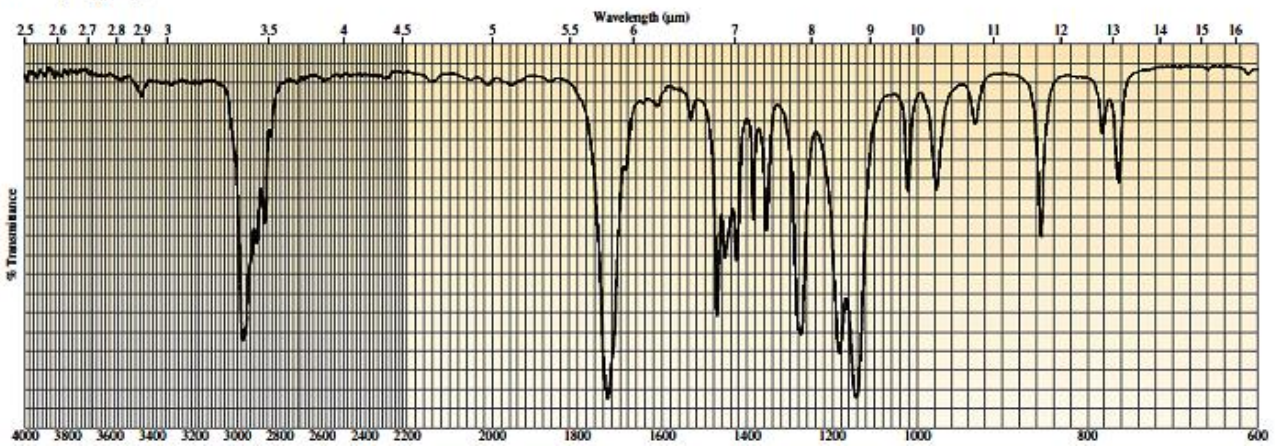


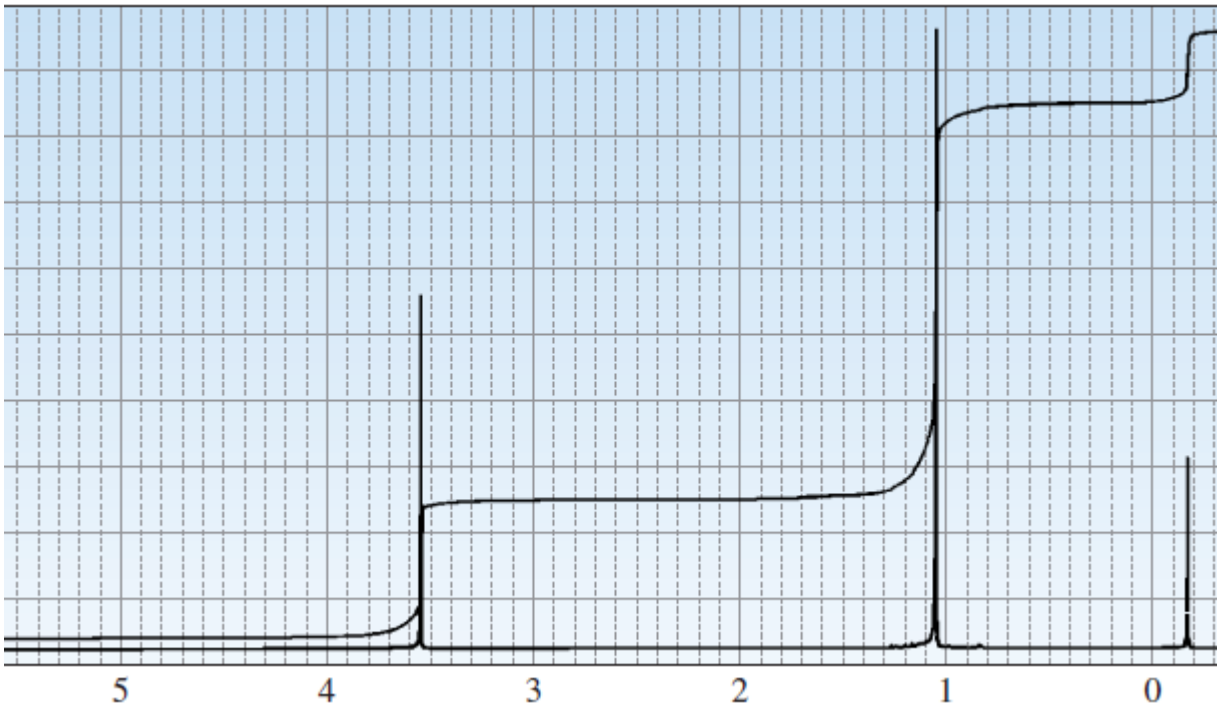
Determine the structure of each of the following unknown compounds based on its molecular formula and  $^1\text{H}$  NMR spectra.

a.  $\text{C}_5\text{H}_{12}\text{O}$

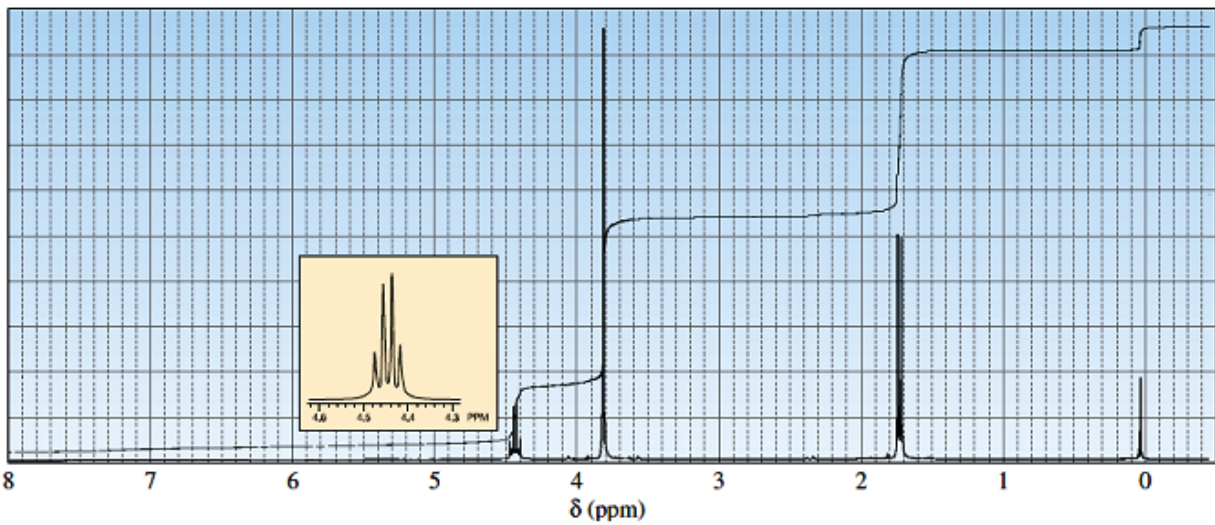
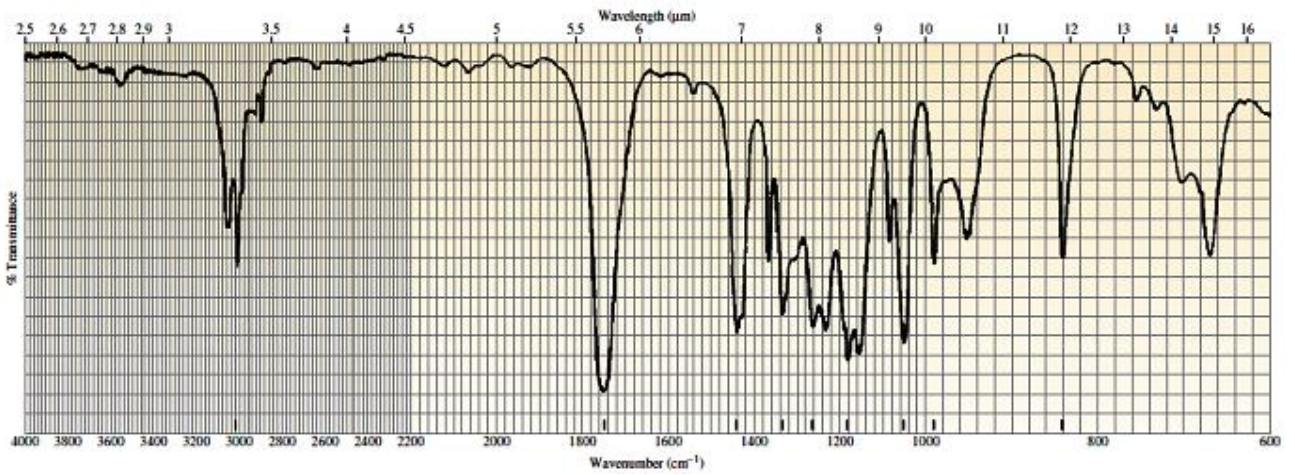


b.  $\text{C}_6\text{H}_{12}\text{O}_2$



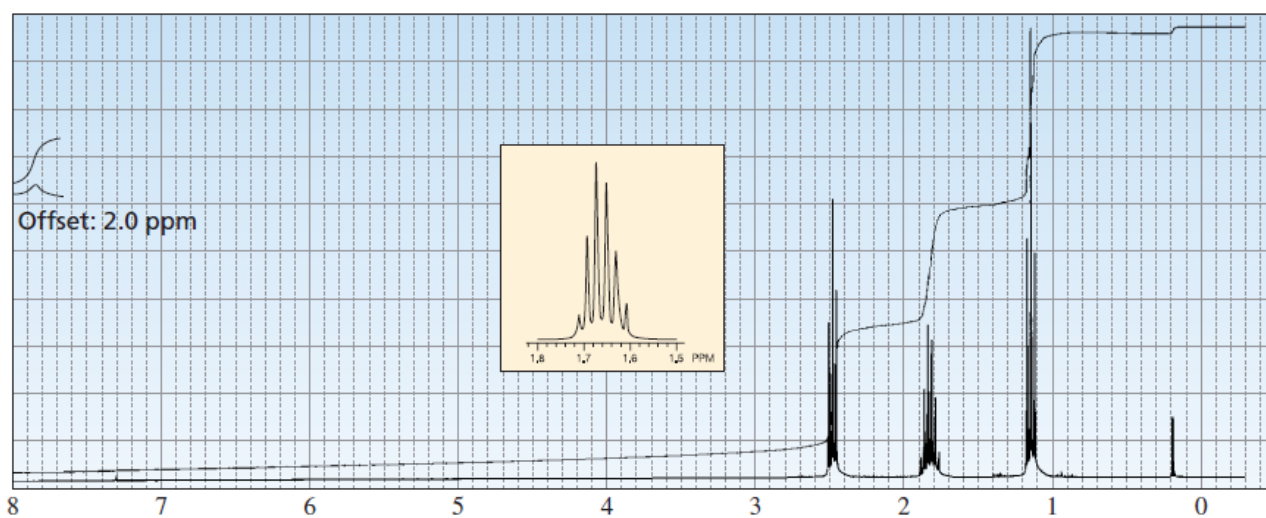
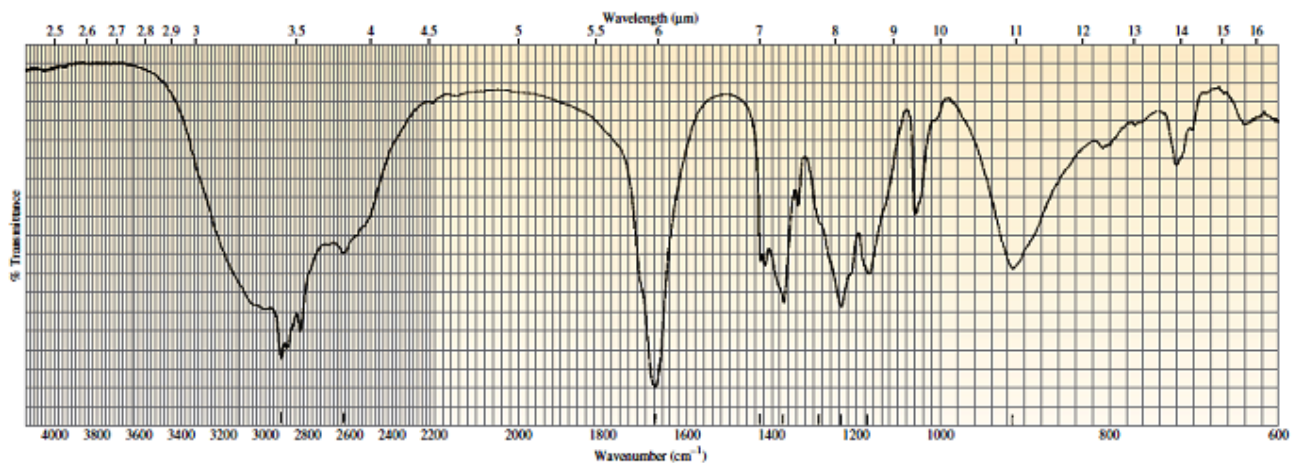


c.  $\text{C}_4\text{H}_7\text{ClO}_2$



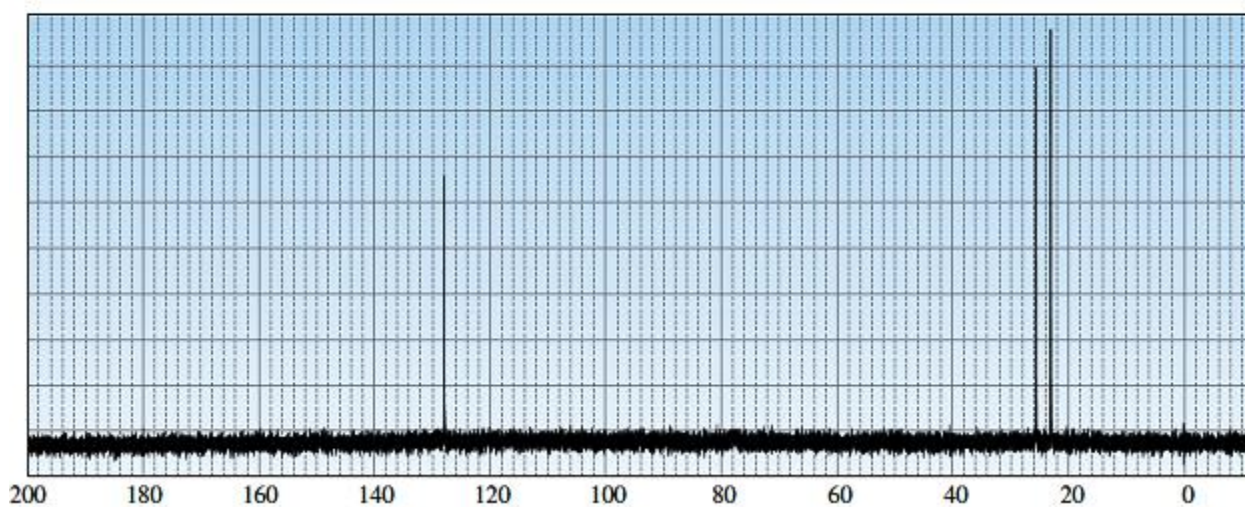


d.  $C_4H_8O_2$

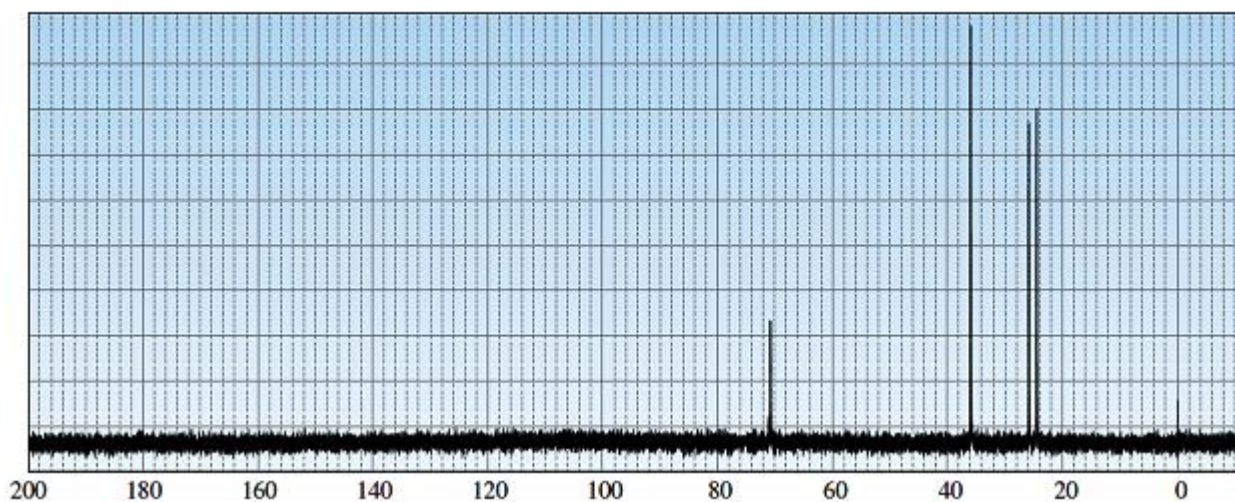


Determine the structure of each of the following compounds based on its molecular formula and its <sup>13</sup>C NMR

a.  $C_4H_{10}O$

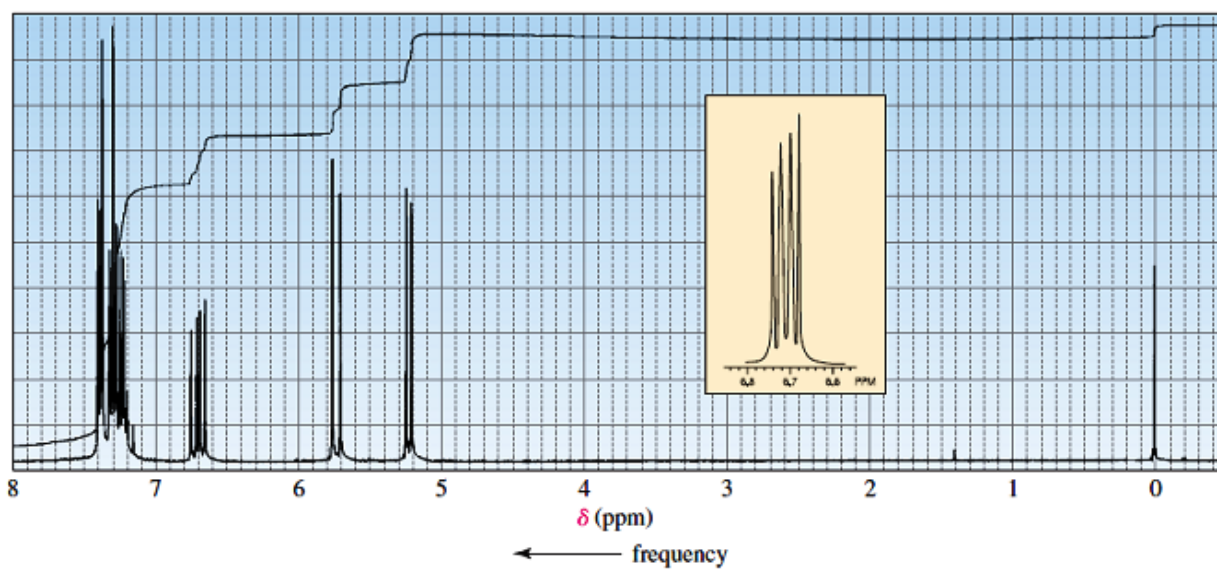


b.  $C_6H_{12}O$



Identify each of the following compounds from its molecular formula and its  $^1H$  NMR spectrum.

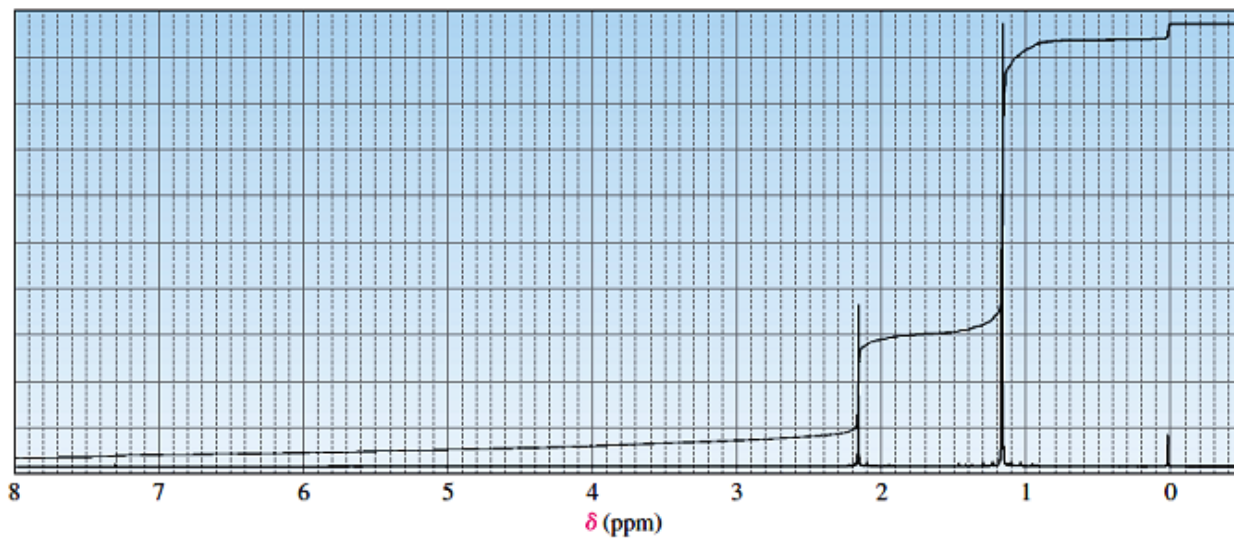
a.  $C_8H_8$



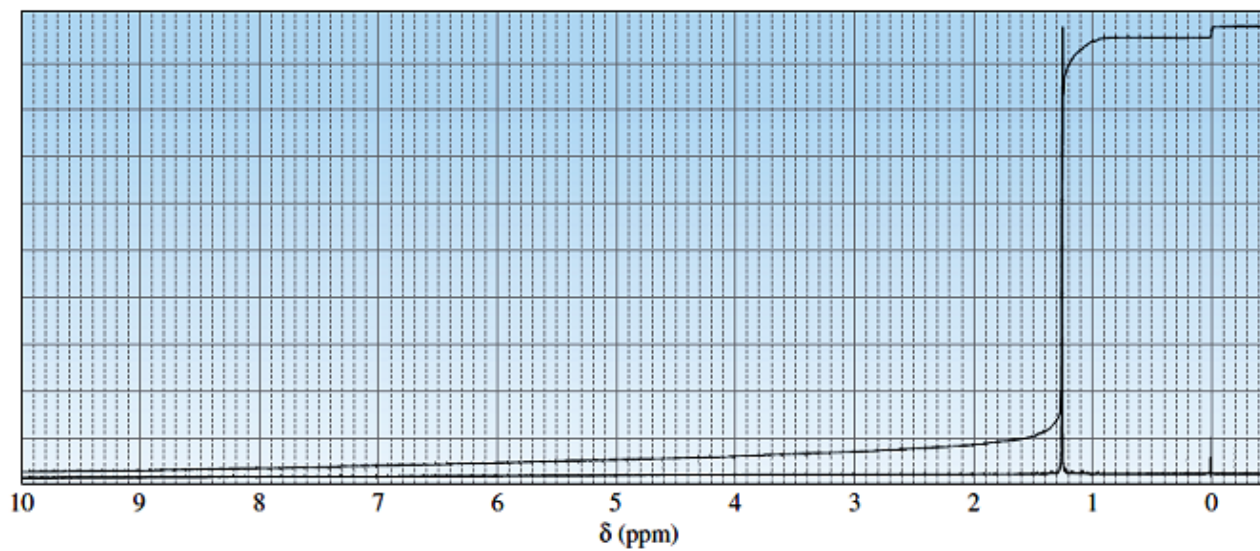
Sketch the following spectra that would be obtained for 2-chloroethanol:

- The  $^1H$  NMR spectrum for a dry sample of the alcohol
- The  $^1H$  NMR spectrum for a sample of the alcohol that contains a trace amount of acid
- The  $^{13}C$  NMR spectrum

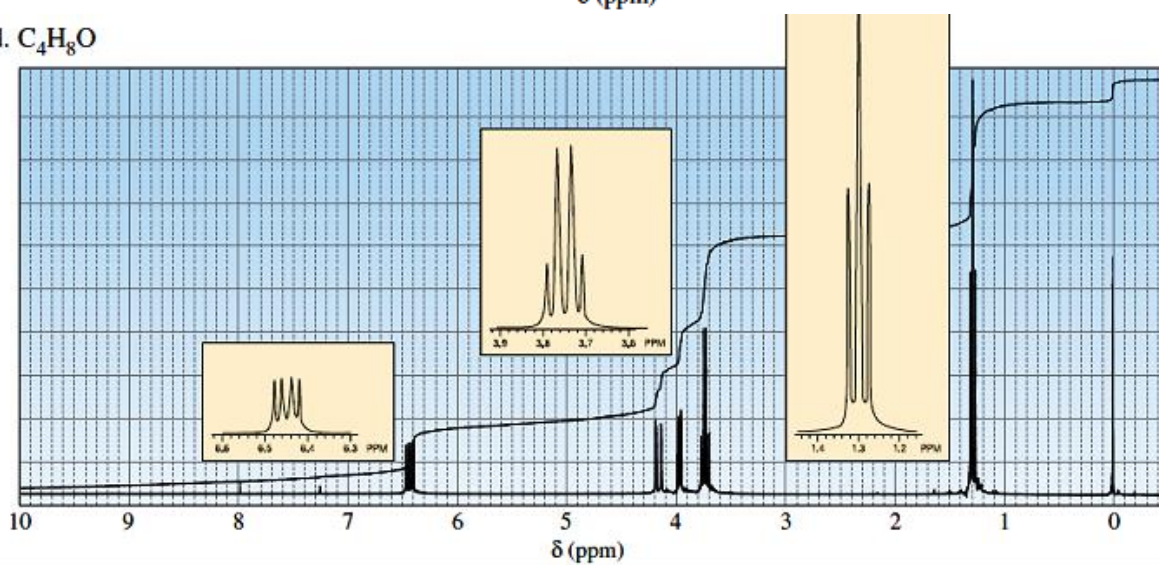
b.  $C_6H_{12}O$



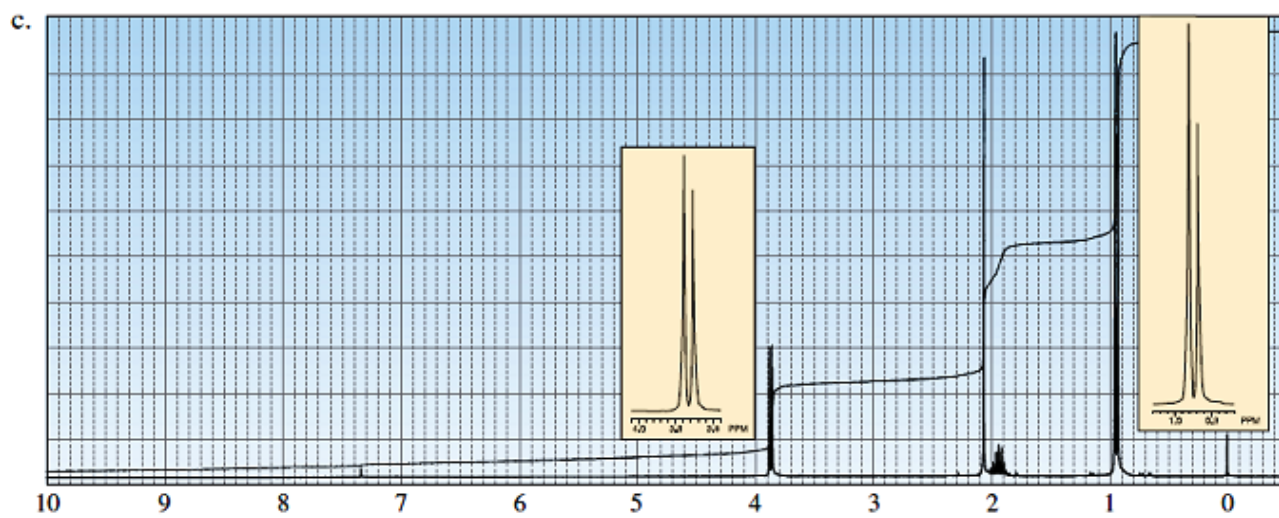
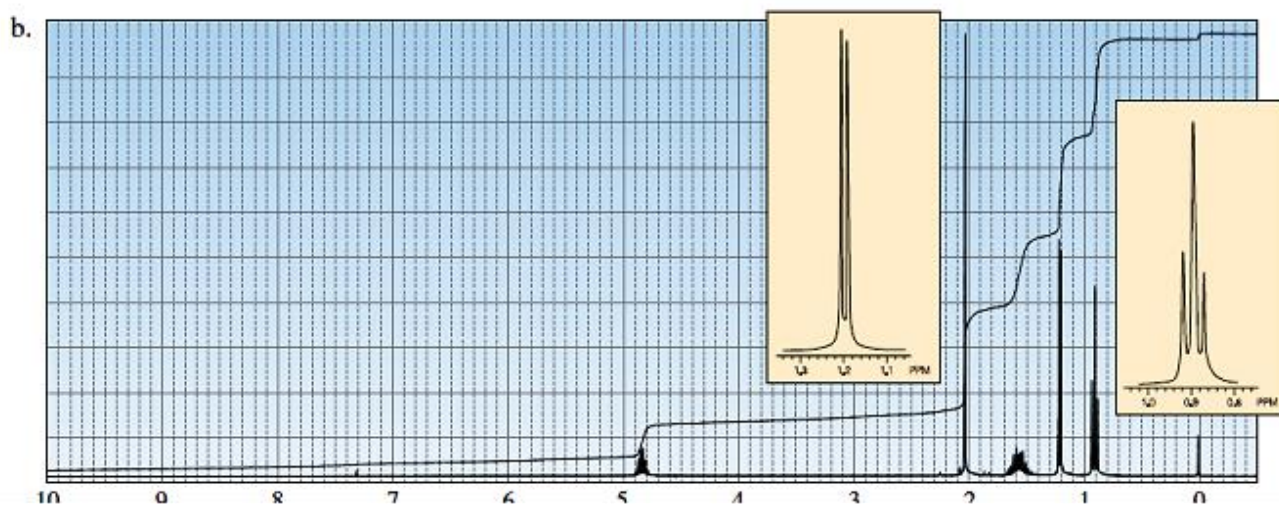
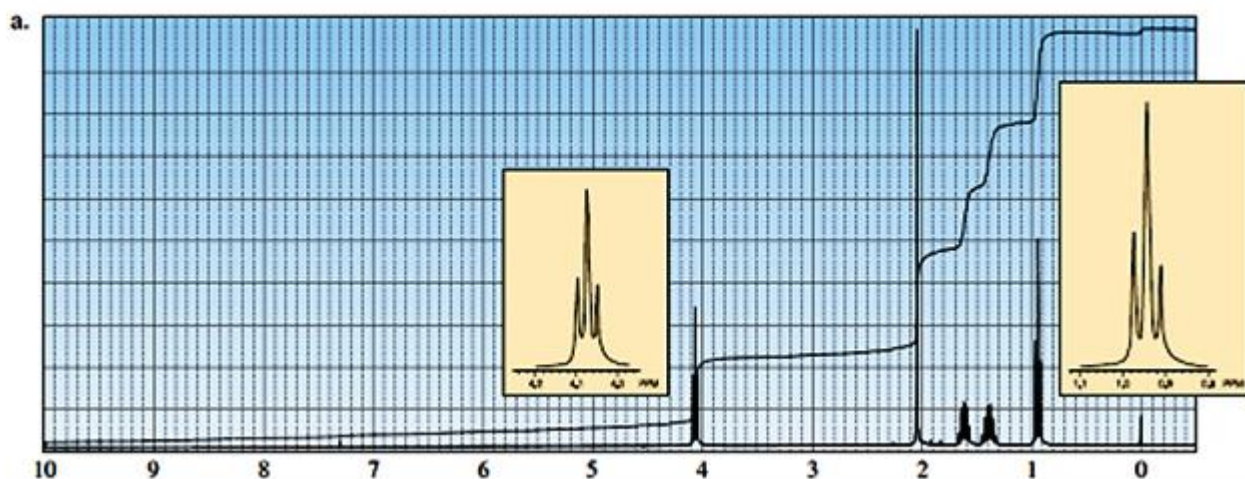
c.  $C_9H_{18}O$

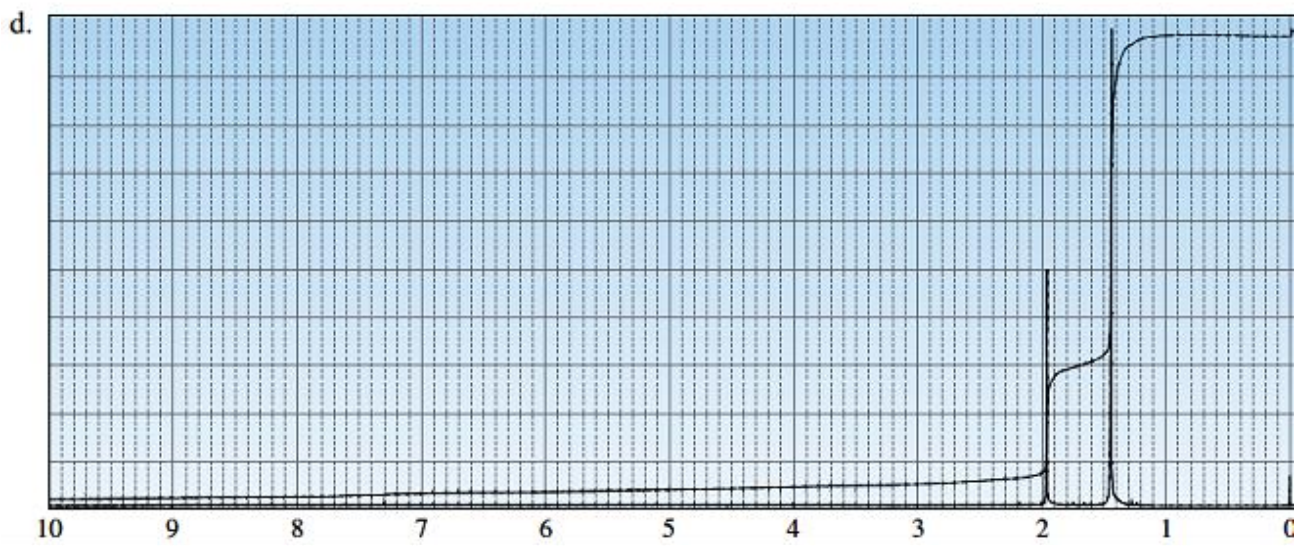


d.  $C_4H_8O$



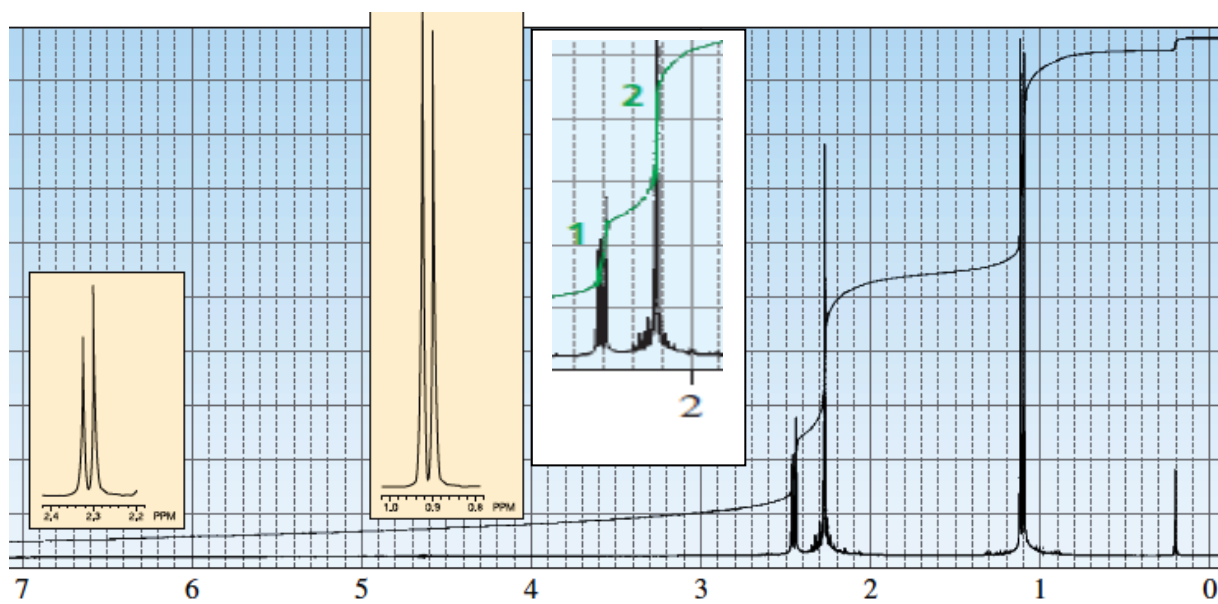
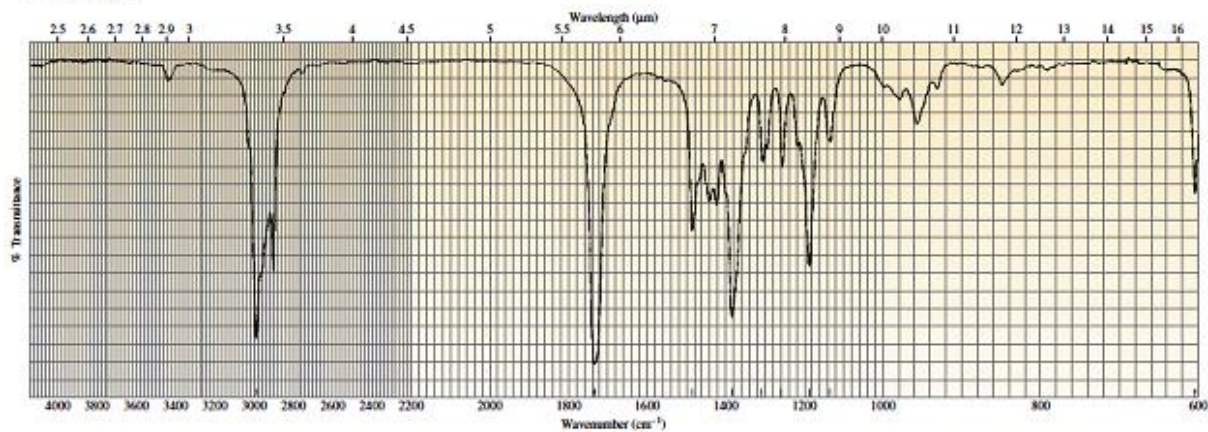
The following  $^1\text{H}$  NMR spectra are for four compounds with molecular formula  $\text{C}_6\text{H}_{12}\text{O}_2$ . Identify the compounds.



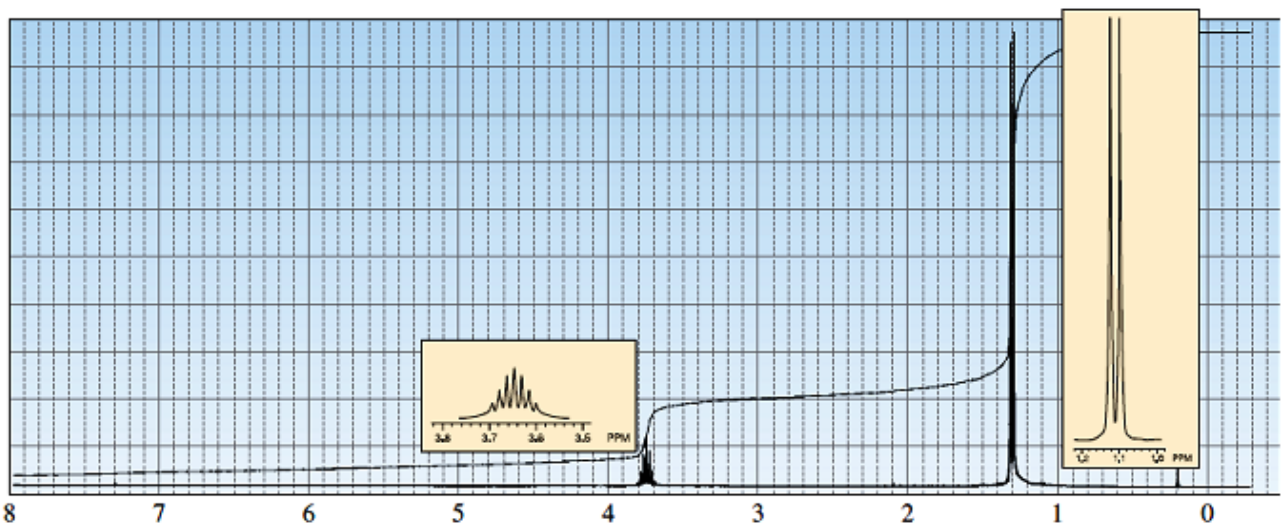
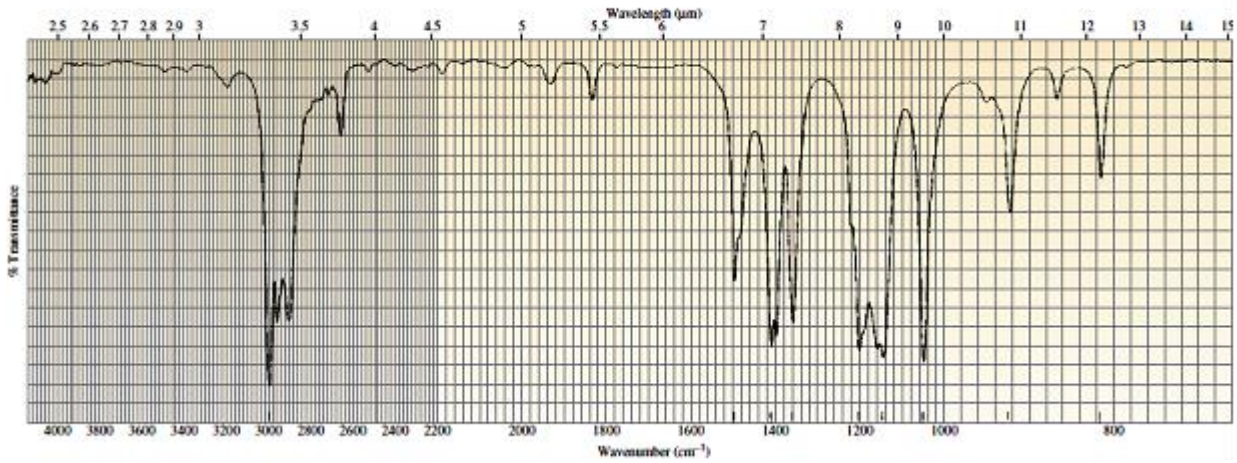


Determine the structure of each of the following compounds based on its molecular formula and its IR and  $^1\text{H}$  NMR :

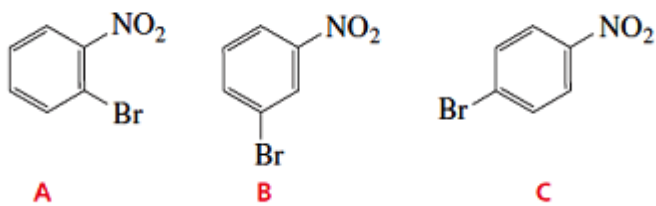
a.  $\text{C}_6\text{H}_{12}\text{O}$



b.  $C_6H_{14}O$



How could <sup>1</sup>H NMR spectra distinguish the following compounds?

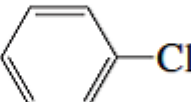


How would the <sup>1</sup>H NMR spectra for the four compounds with molecular formula  $C_3H_6Br_2$  differ?

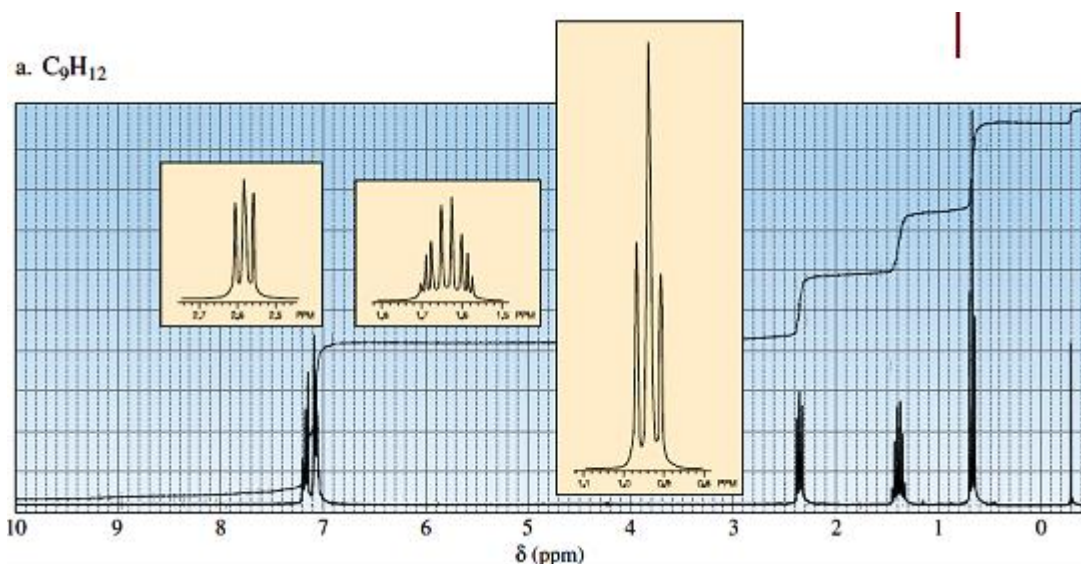
Answer the following questions for each of the compounds:

a. How many signals are in the  $^{13}\text{C}$  NMR spectrum?

b. Which signal is at the lowest frequency?

- |   |   |  |
|---|---|--|
| 1. $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br}$ | 5. $\text{CH}_3\text{CH}_2\overset{\text{O}}{\parallel}\text{COCH}_3$   | 9. $\begin{array}{c} \text{CH}_3 \\   \\ \text{CH}_3\text{COCH}_3 \\   \\ \text{CH}_3 \end{array}$ |
| 2. $(\text{CH}_3)_2\text{C}=\text{CH}_2$        | 6. $\begin{array}{c} \text{O} \\ \parallel \\ \text{CH}_3\text{CHCH} \\   \\ \text{CH}_3 \end{array}$         | 10. $\begin{array}{c} \text{CH}_3\text{CHCH}_3 \\   \\ \text{Br} \end{array}$                      |
| 3. $\text{CH}_3\text{CH}_2\text{OCH}_3$         | 7.                           |  |
| 4. $\text{CH}_2=\text{CHBr}$                    | 8. $\text{CH}_3\overset{\text{O}}{\parallel}\text{CCH}_2\text{CH}_2\overset{\text{O}}{\parallel}\text{CCH}_3$ |  |

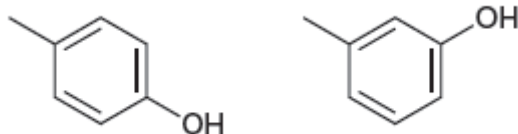
Identify each compound from its molecular formula and its  $^1\text{H}$  NMR spectrum:



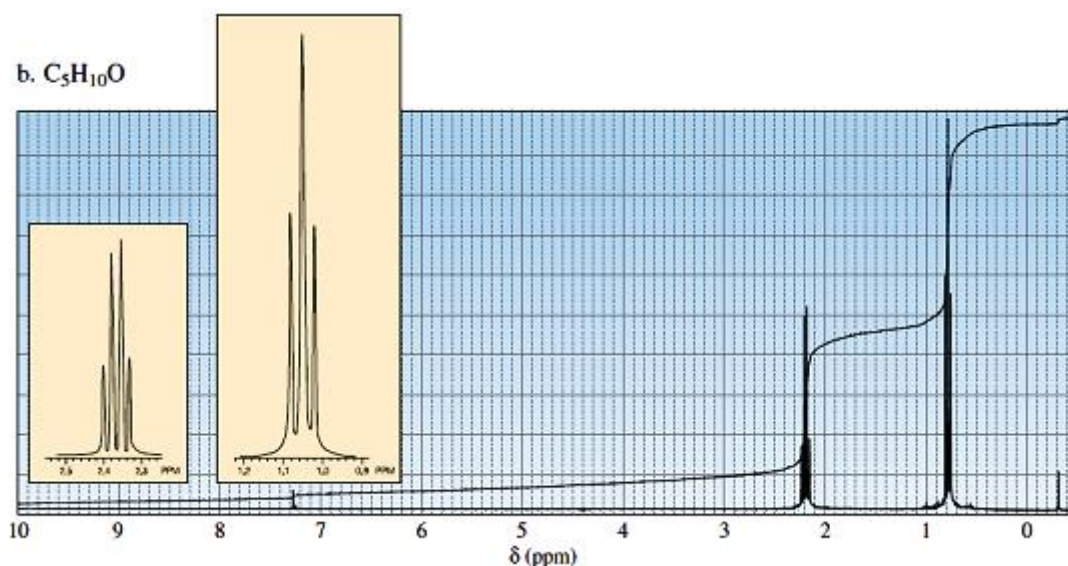
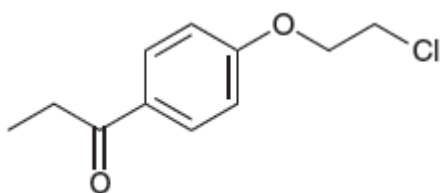
Q- A compound with molecular formula  $C_{17}H_{36}$  exhibits a  $^1H$  NMR spectrum with only one signal. How many signals would you expect in the  $^{13}C$  NMR spectrum of this compound?

Q- A compound with molecular formula  $C_8H_{18}$  exhibits a  $^1H$  NMR spectrum with only one signal. How many signals would you expect in the  $^{13}C$  NMR spectrum of this compound?

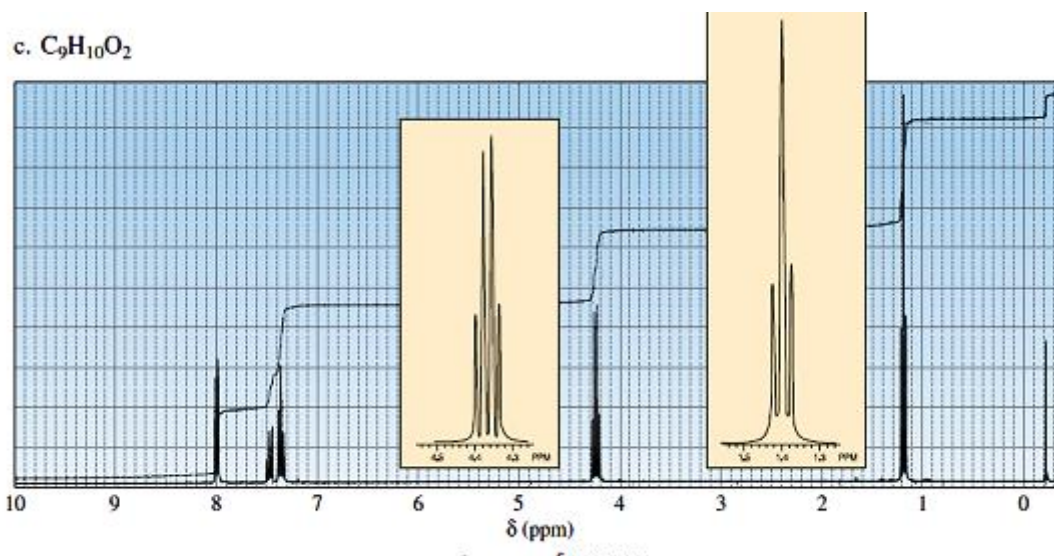
Q- How would you distinguish between the following compounds using  $^{13}C$  NMR spectroscopy?



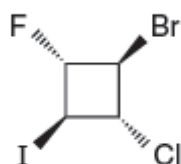
Q- Draw the expected  $^1H$  NMR spectrum of the following compound:







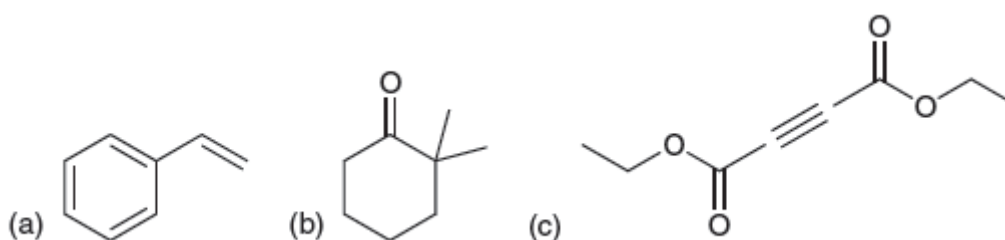
Q- Consider the following compound:



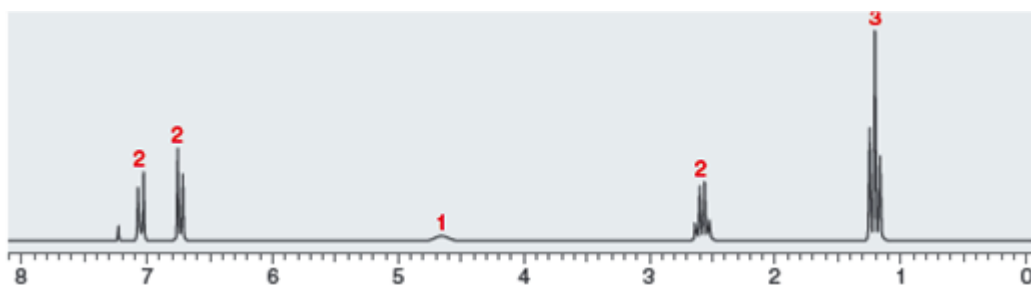
- How many signals do you expect in the  $^1H$  NMR spectrum of this compound?
- Rank the protons in terms of increasing chemical shift.
- How many signals do you expect in the  $^{13}C$  NMR spectrum?
- Rank the carbon atoms in terms of increasing chemical shift.

Q- A compound with molecular formula  $C_9H_{18}$  exhibits a  $^1H$  NMR spectrum with only one signal and a  $^{13}C$  NMR spectrum with two signals. Deduce the structure of this compound.

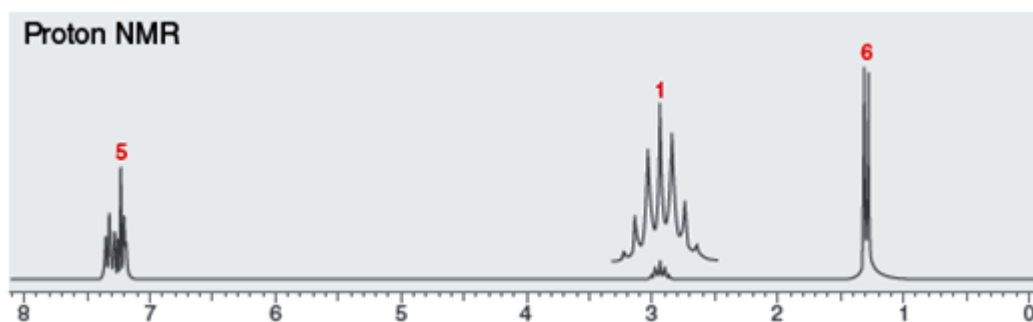
Q- Predict the expected number of signals in the  $^{13}C$  NMR spectrum of each of the following compounds. For each signal, identify where you expect it to appear in the  $^{13}C$  NMR spectrum:



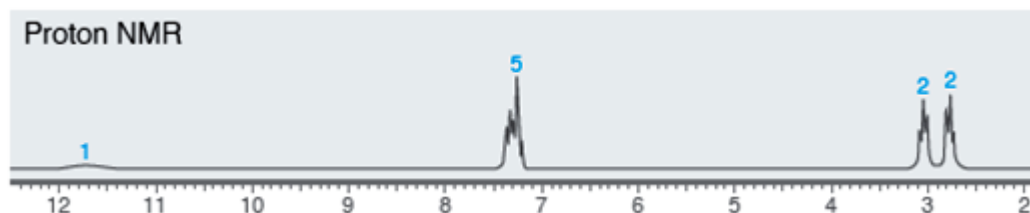
Q- A compound with molecular formula  $C_8H_{10}O$  produces six signals in its  $^{13}C$  NMR spectrum and exhibits the following  $^1H$  NMR spectrum. Deduce the structure of the compound.



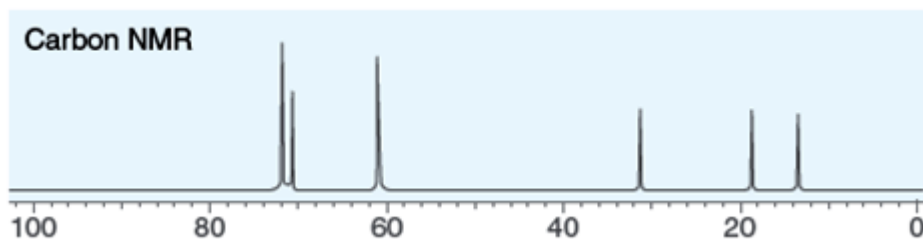
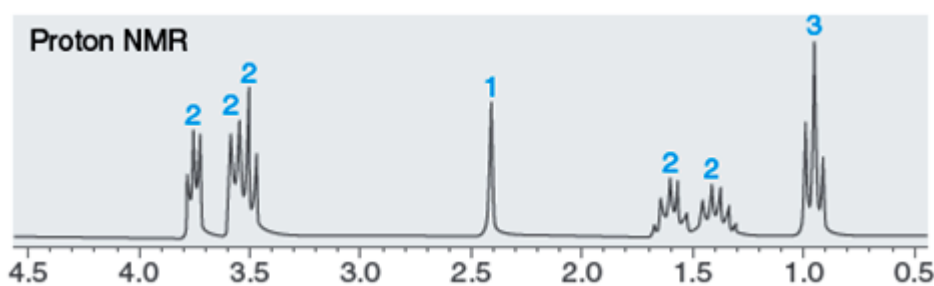
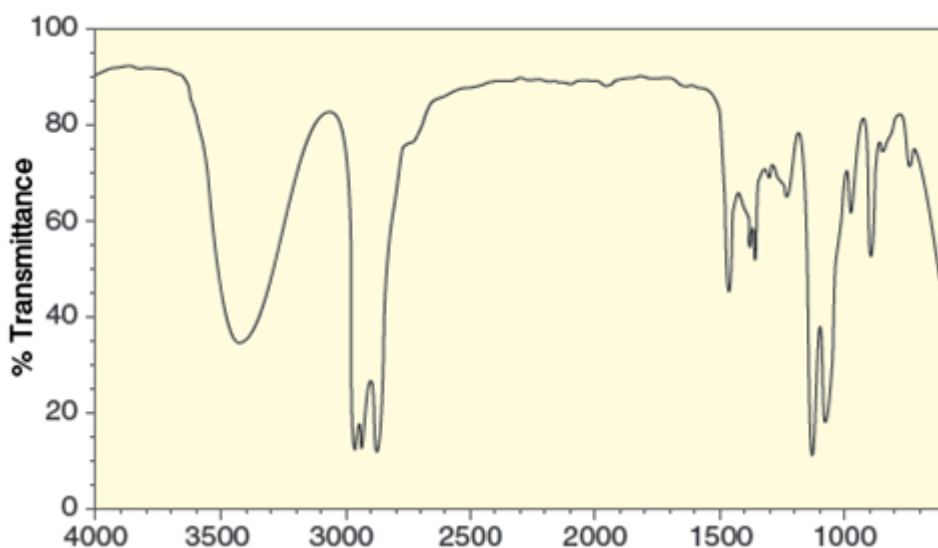
Q- Deduce the structure of a compound with molecular formula  $C_9H_{12}$  that produces the following  $^1H$  NMR spectrum:



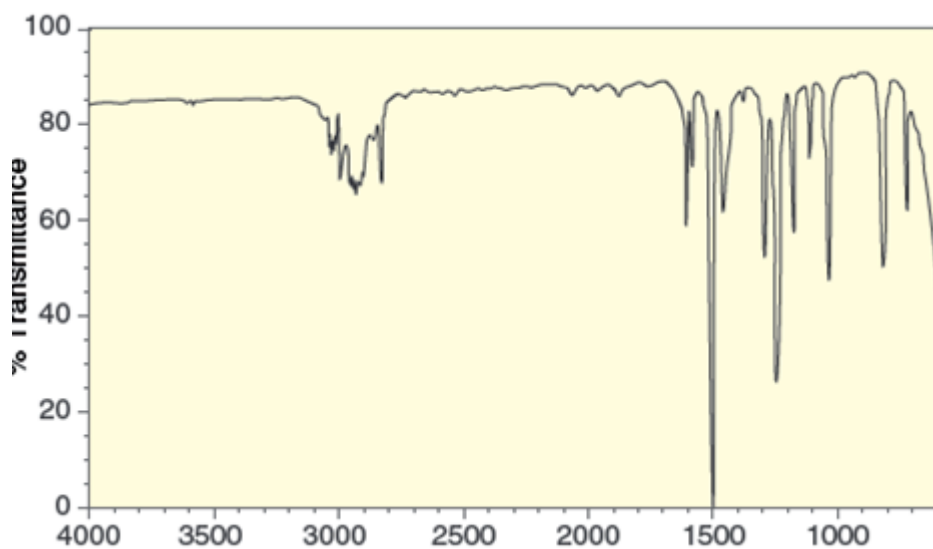
Q- Deduce the structure of a compound with molecular formula  $C_9H_{10}O_2$  that produces the following  $^1H$  NMR spectrum and  $^{13}C$  NMR spectrum:

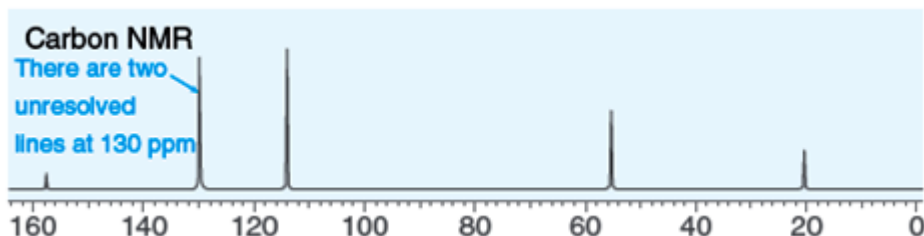
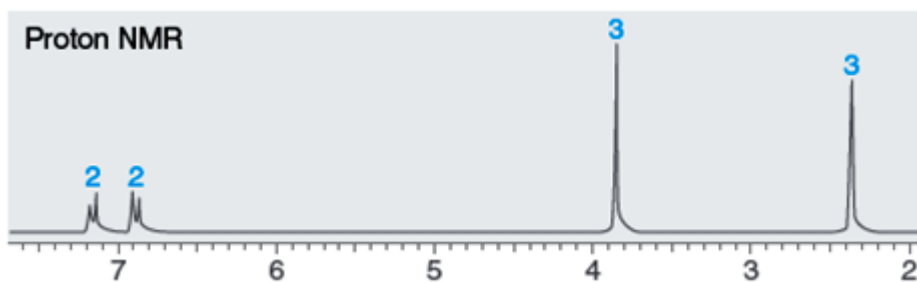


Q- Deduce the structure of a compound with molecular formula  $C_6H_{14}O_2$  that exhibits the following IR,  $^1H$  NMR, and  $^{13}C$  NMR spectra:

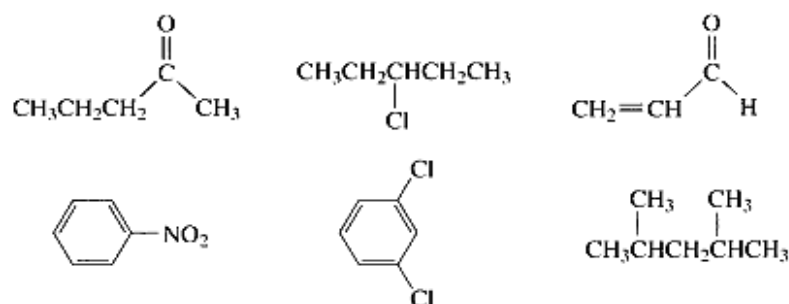


Q- Deduce the structure of a compound with molecular formula  $C_8H_{10}O$  that exhibits the following IR,  $^1H$  NMR, and  $^{13}C$  NMR spectra:

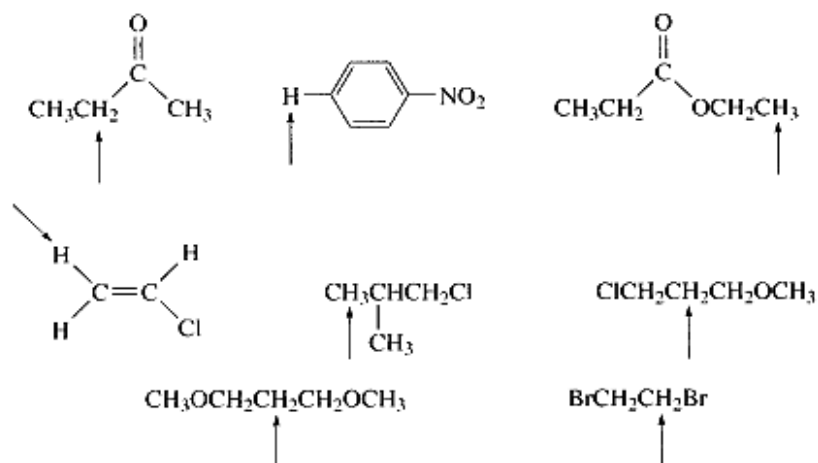




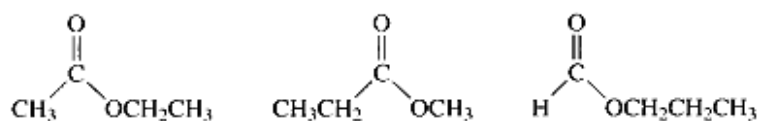
1. How many signals would you expect to see in the  $^1\text{H}$  NMR spectrum of each of the following compounds?



2. Indicate the multiplicity of each of the indicated sets of protons. (That is, indicate whether it is a singlet, doublet, triplet, quartet, quintet, multiplet, or doublet of doublets.)

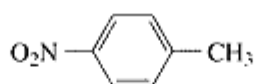


3. How could you distinguish the following compounds using  $^1\text{H}$  NMR spectroscopy?

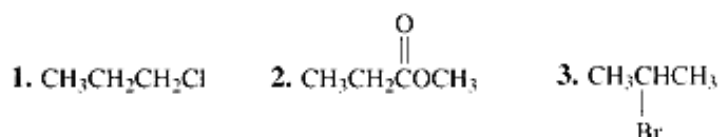


Indicate whether each of the following statements is true or false:

- a. The signals on the right of an NMR spectrum are deshielded compared to the signals on the left. T    F
- b. Dimethyl ketone has the same number of signals in its  $^1\text{H}$  NMR spectrum as in its  $^{13}\text{C}$  NMR spectrum. T    F
- c. In the  $^1\text{H}$  NMR spectrum of the compound shown below, the lowest frequency signal (the one farthest upfield) is a singlet and the highest frequency signal (the one farthest downfield) is a doublet. T    F

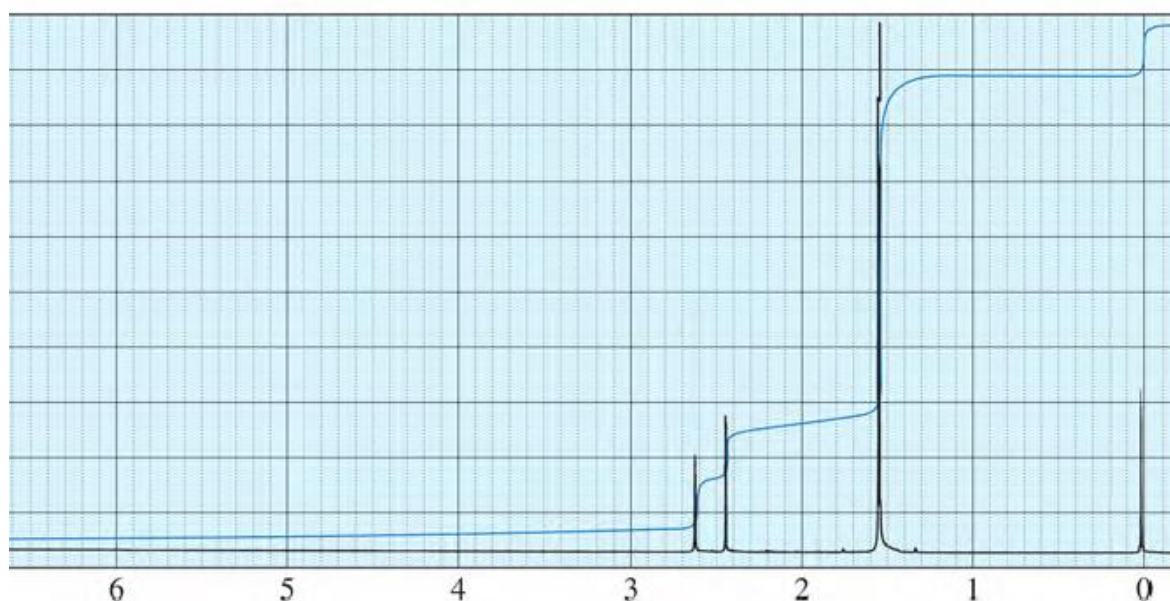
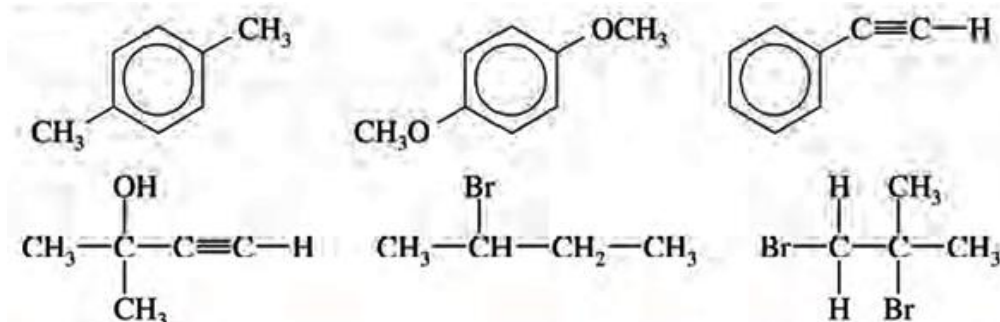


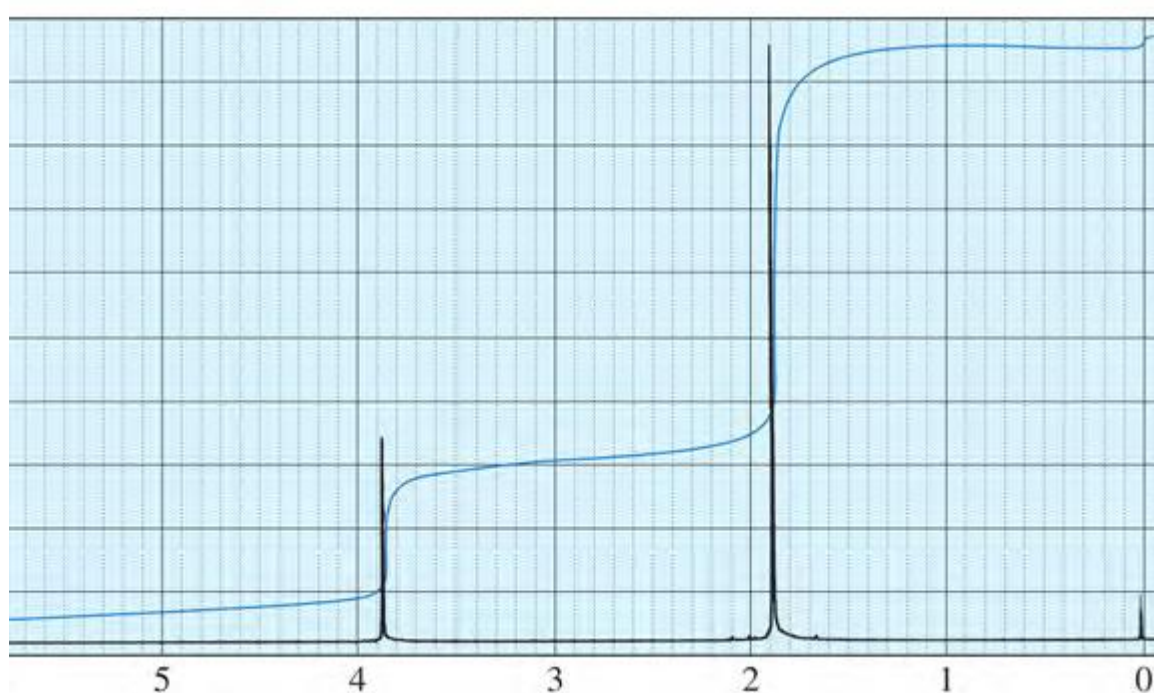
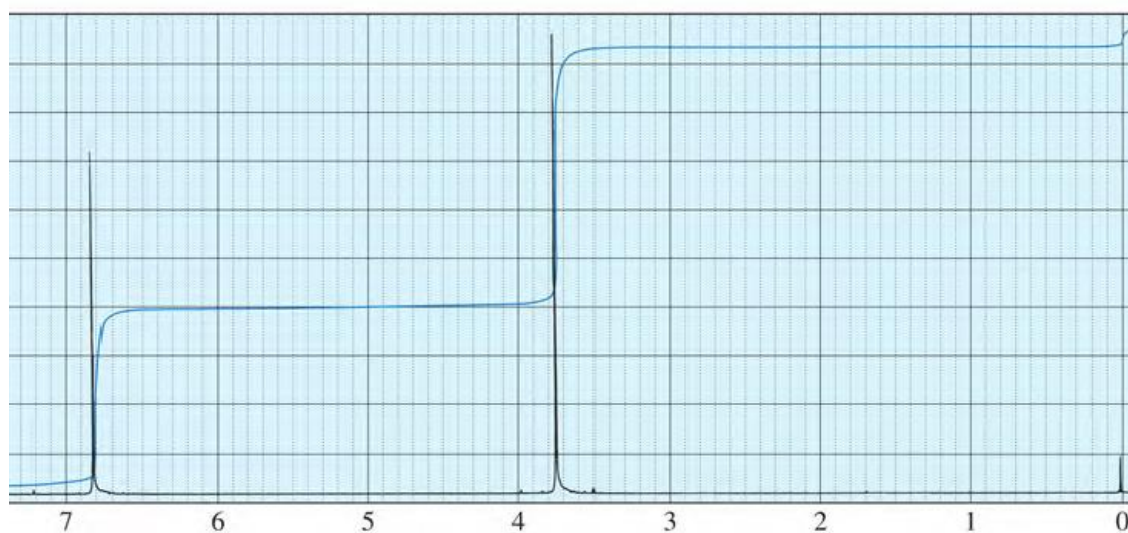
- d. The greater the frequency of the signal, the greater its chemical shift in ppm. T    F



6. For each compound of Problem 5:

- a. Indicate the number of signals you would expect to see in its  $^{13}\text{C}$  NMR spectrum.  
 b. Indicate the carbon that would give the highest frequency (farthest downfield) signal.



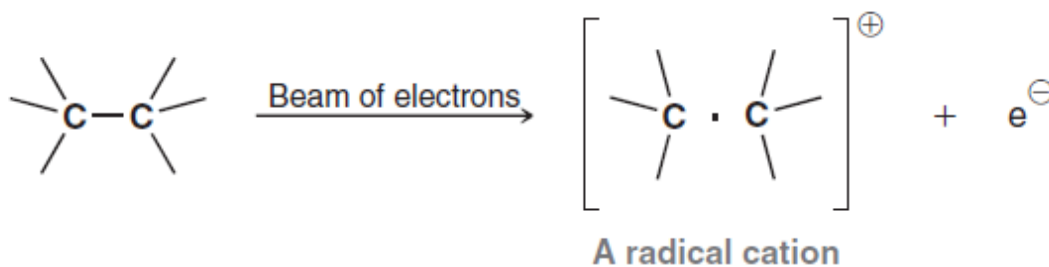


## Mass spectrometry

**Mass spectrometry** allows us to determine the *molecular mass* and the *molecular formula* of a compound, as well as certain *structural features* of the compound. Spectroscopy is the study of the interaction between matter and electromagnetic radiation. In contrast, **mass spectrometry** is the study of the interaction between matter and an energy source other than electromagnetic radiation.

In mass spectrometry, a small sample of a compound is introduced into an instrument called a mass spectrometer, where it is vaporized and then ionized, converted into ions, which are then separated and detected. The most common ionization technique

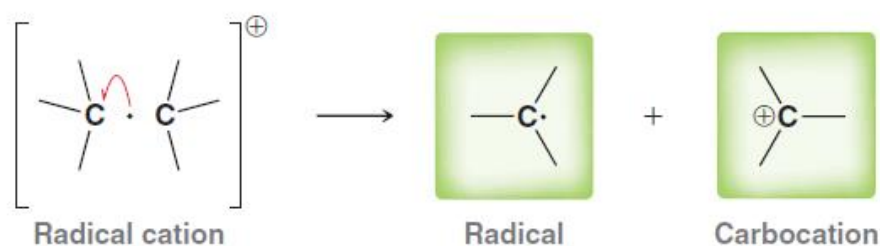
involves bombarding the compound with high-energy electrons. These electrons carry an extraordinary amount of energy, usually around 1600 kcal/mol, or 70 electron volts (eV). When a high-energy electron strikes the molecule, it causes one of the electrons in the molecule to be ejected. This technique, called electron impact ionization (EI), generates a high-energy intermediate that is both a radical and a



cation

It is a radical because it has an unpaired electron, and it is a cation because it bears a positive charge as a result of losing an electron. The mass of the ejected electron is negligible compared to the mass of the molecule, so the mass of the radical cation is essentially equivalent to the mass of the original molecule. This radical cation, symbolized by  $(M)^{+\bullet}$ , is called the **molecular ion**.

The molecular ion is often very unstable and is susceptible to **fragmentation**, which generates two distinct fragments. Most commonly, one fragment carries the unpaired electron, while the other fragment carries the charge.



In this way, the ionization process generates many different cations—the molecular ion as well as many different carbocation fragments. All of these ions are accelerated and then sent through a magnetic field, where they are deflected in curved paths. The uncharged radical fragments are not deflected by the magnetic field and are therefore not detected by the mass spectrometer.

Not surprisingly, the bonds most likely to break are the weakest ones and those that result in the formation of the most stable products. All the *positively charged*

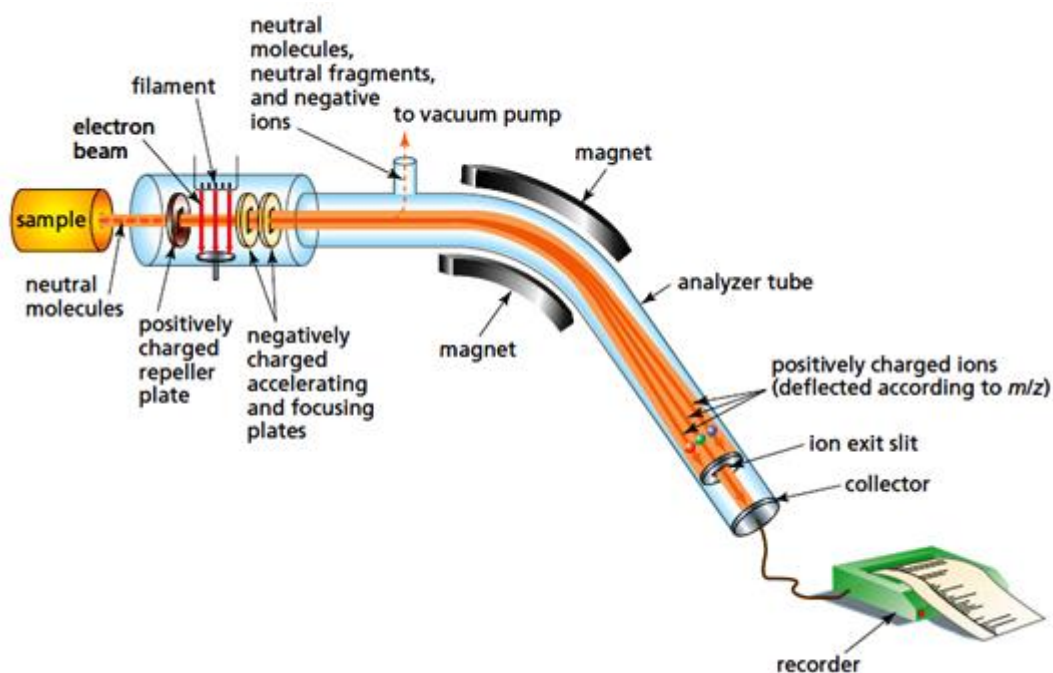
fragments of the molecule pass between two negatively charged plates, which accelerate the fragments into an analyzer tube. Neutral fragments pumped out of the spectrometer.

The analyzer tube is surrounded by a magnet whose magnetic field deflects the positively charged fragments in a curved path. At a given magnetic field strength, the degree to which the path is curved depends on the mass-to-charge ratio ( $m/z$ ) of the fragment: The path of a fragment with a smaller  $m/z$  value will bend more than that of a heavier fragment.

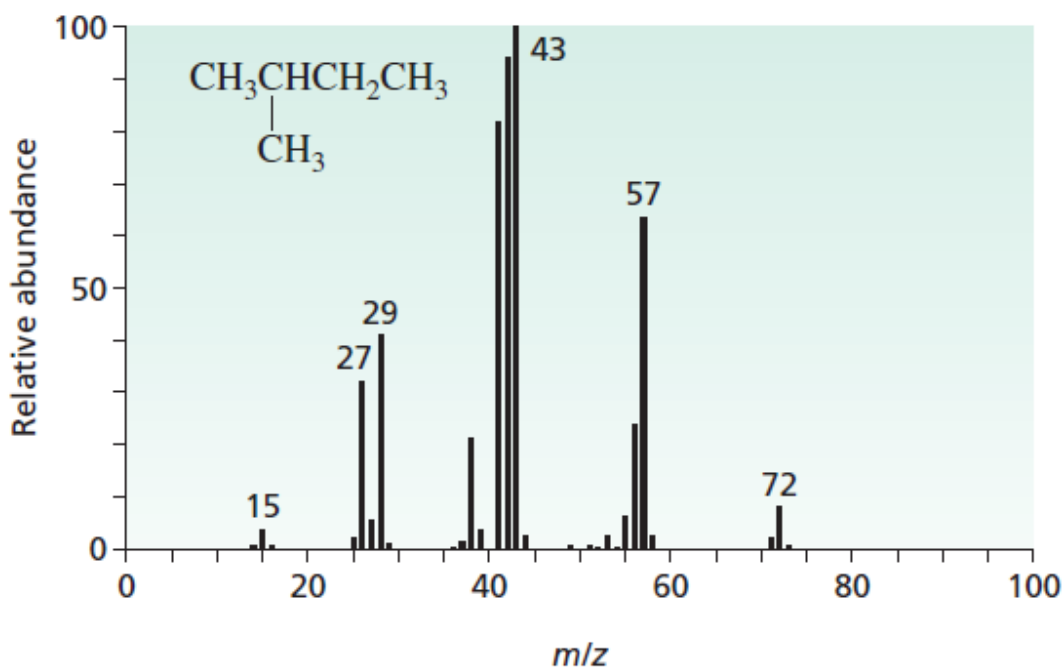
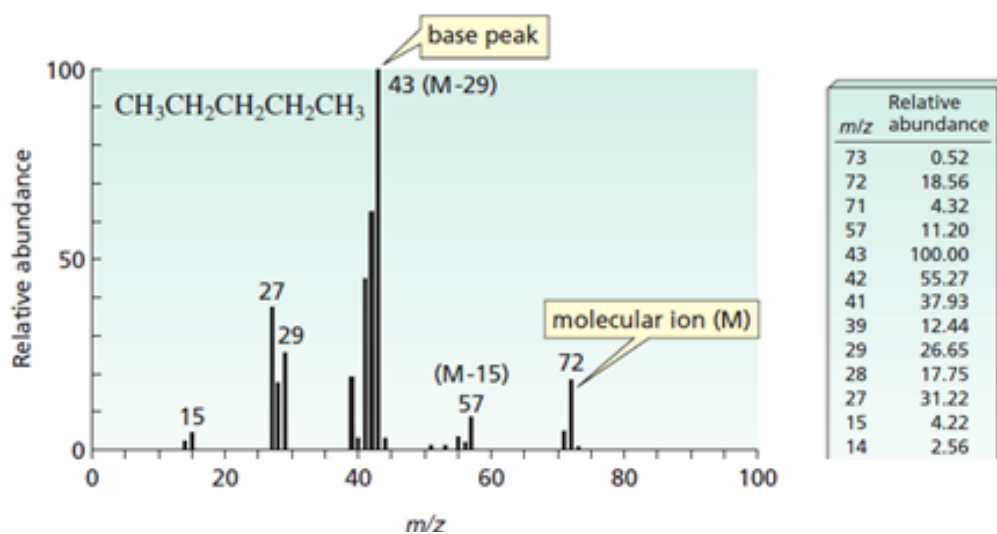
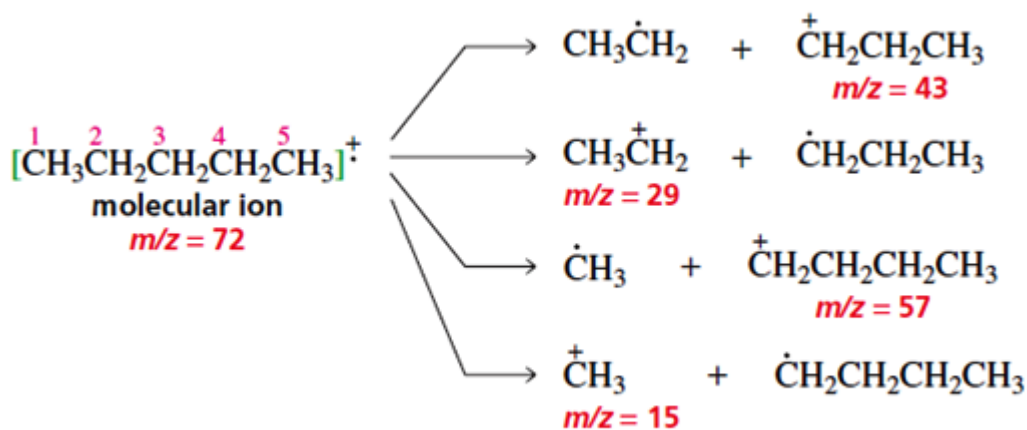
A collector records the relative number of fragments with a particular  $m/z$  passing through the slit. The strength of the magnetic field is gradually increased, so fragments with progressively larger  $m/z$  values are guided through the tube and out the exit slit.

The mass spectrometer records a **mass spectrum**—a graph of the relative abundance of each fragment plotted against its  $m/z$  value. Because the charge ( $z$ ) on essentially all the fragments that reach the collector plate is +1,  $m/z$  is the molecular mass ( $m$ ) of the fragment.

The tallest peak in the spectrum is assigned a relative value of 100% and is called the base peak.







The C-C bonds in the molecular ion formed from pentane have about the same strength. However, the bond C2-C3 is more likely to break than the C1-C2 bond

because C2-C3 fragmentation leads to a *primary* carbocation and a *primary* radical, which together are more stable than the *primary* carbocation and *methyl* radical (or *primary* radical and *methyl* cation) obtained from C1-C2 fragmentation. C2-C3 fragmentation forms ions with  $m/z = 43$  or  $29$ , and C1-C2 fragmentation forms ions with  $m/z = 57$  or  $15$ . The base peak of  $43$  in the mass spectrum of pentane indicates the preference for C2-C3 fragmentation

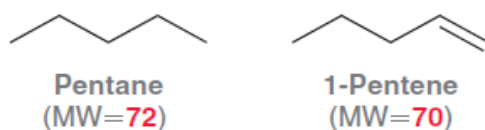
A method commonly used to identify fragment ions is to determine the difference between the  $m/z$  value of a given fragment ion and that of the molecular ion.

Peaks are commonly observed at  $m/z$  values one and two units less than the  $m/z$  values of the carbocations because the carbocations can undergo further fragmentation—losing one or two hydrogen atoms

Q1: How could you distinguish the mass spectrum of 2,2-dimethylpropane from those of pentane and 2-methylbutane?

Q2: What  $m/z$  value is most likely for the base peak in the mass spectrum of 3-methylpentane?

When analyzing a mass spectrum, the first step is to look for the  $(M)^{+•}$  peak, because it indicates the molecular weight of the molecule. This technique can be used to distinguish compounds. For example, compare the molecular weights of pentane and of 1-pentene



Pentane has 5 carbon atoms ( $5 \times 12 = 60$ ) and 12 hydrogen atoms ( $12 \times 1 = 12$ ) and therefore a molecular weight of 72. In contrast, 1-pentene only has 10 hydrogen atoms and therefore has a molecular weight of 70.

Useful information can also be obtained by analyzing whether the molecular weight of the parent ion is odd or even. An odd molecular weight generally indicates an odd number of nitrogen atoms in the compound, while an even molecular weight indicates

either the absence of nitrogen or an even number of nitrogen atoms. This is called the **nitrogen rule**, and it is illustrated in the following examples:

0 nitrogen atoms



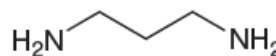
MW=72  
(even number)

1 nitrogen atom



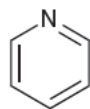
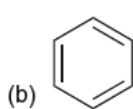
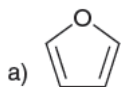
MW=73  
(odd number)

2 nitrogen atoms

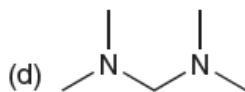
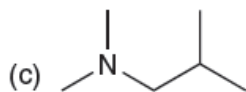
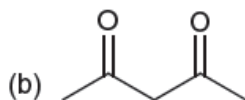
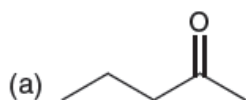


MW=74  
(even number)

- How would you distinguish between each pair of compounds using mass spectrometry?



- For each of the following compounds, use the nitrogen rule to determine whether the molecular weight should be even or odd. Then calculate the expected  $m/z$  value for the molecular ion



Which peak would be more intense in the mass spectrum of the following compounds—the peak at  $m/z = 57$  or the peak at  $m/z = 71$ :

a. 3-methylpentane

b. 2-methylpentane

- The “Rule of Thirteen” can be used to identify possible molecular formulas for an unknown hydrocarbon,  $C_nH_m$ .
  - Step 1:  $n = M^+/13$  (integer only, use remainder in step 2)
  - Step 2:  $m = n + \text{remainder from step 1}$
- Example: The formula for a hydrocarbon with  $M^+ = 106$  can be found:
  - Step 1:  $n = 106/13 = 8$  ( $R = 2$ )
  - Step 2:  $m = 8 + 2 = 10$
  - Formula:  $C_8H_{10}$

- If a heteroatom is present,
  - Subtract the mass of each heteroatom from the MW
  - Calculate the formula for the corresponding hydrocarbon
  - Add the heteroatoms to the formula
- Example: A compound with a molecular ion peak at  $m/z = 102$  has a strong peak at  $1739\text{ cm}^{-1}$  in its IR spectrum. Determine its molecular formula.

Determine the molecular formula for each of the following:

- a compound that contains only C and H and has a molecular ion with an  $m/z$  value of 72
- a compound that contains C, H, and one O and has a molecular ion with an  $m/z$  value of 100
- a compound that contains C, H, and two Os and has a molecular ion with an  $m/z$  value of 102
- an amide that has a molecular ion with an  $m/z$  value of 115

What hydrocarbons will have a molecular ion peak at  $m/z = 112$

Q: Determine the molecular formula of a saturated acyclic hydrocarbon with an M peak at  $m/z = 100$  with a relative intensity of 27.32%, and an  $M + 1$  peak with a relative intensity of 2.10%.

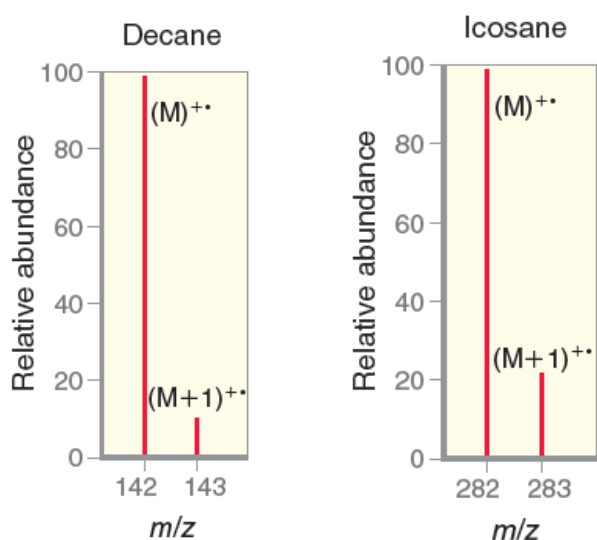
## Isotopes in Mass Spectrometry

Although the molecular ions of pentane and 2-methylbutane both have  $m/z$  values of 72, each spectrum shows a very small peak at  $m/z = 73$

This peak is called an  $M+1$  peak because the ion responsible for it is one unit heavier than the molecular ion. The peak owes its presence to the fact that there are two naturally occurring isotopes of carbon: 98.89% of natural carbon is  $^{12}\text{C}$  and 1.11% is  $^{13}\text{C}$ .

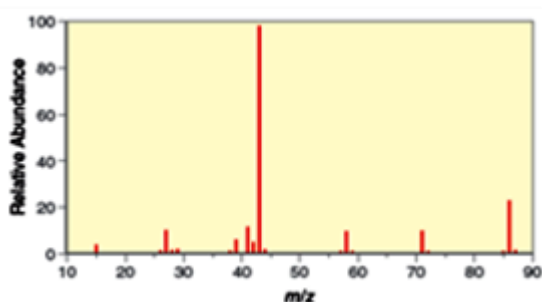
So 1.11% of the molecular ions contain a  $^{13}\text{C}$  instead of a  $^{12}\text{C}$  and therefore appear at  $M+1$ . In a mass spectrometer, each individual molecule is ionized and then passed through the magnetic field. When methane is analyzed, 98.9% of the molecular ions will contain a  $^{12}\text{C}$  atom, while only 1.1% will contain a  $^{13}\text{C}$  atom. The latter group

of molecular ions are responsible for the observed peak at  $(M+1)^+$ . The relative height of this peak is approximately 1.1% as tall as the  $(M)^+$  peak, just as expected. Larger compounds, containing more carbon atoms, will have a larger  $(M+1)^+$  peak. For example, decane has 10 carbon atoms in its structure, so the chances that a molecule of decane will possess one  $^{13}\text{C}$  atom are 10 times greater than the chances that a molecule of methane will possess a  $^{13}\text{C}$  atom. Consequently, the  $(M+1)^+$  peak in the mass spectrum of decane is 11% as tall as the molecular ion peak (10  $\times$  1.1%). Similarly, the  $(M+1)^+$  peak in the mass spectrum of icosane ( $\text{C}_{20}\text{H}_{42}$ ) is 22% as tall as the molecular ion peak (20  $\times$  1.1%)



Below is the mass spectrum as well as the tabulated mass spectrum data for an unknown compound. Propose a molecular formula for this compound

| MASS SPECTRUM DATA |                     |       |                     |
|--------------------|---------------------|-------|---------------------|
| $m/z$              | RELATIVE HEIGHT (%) | $m/z$ | RELATIVE HEIGHT (%) |
| 15                 | 4.8                 | 42    | 4.0                 |
| 26                 | 1.3                 | 43    | 100 (base peak)     |
| 27                 | 10.5                | 44    | 2.3                 |
| 28                 | 1.3                 | 58    | 10.3                |
| 29                 | 1.9                 | 71    | 11.0                |
| 38                 | 1.2                 | 86    | 20.9 ( $M^+$ )      |
| 39                 | 6.3                 | 87    | 1.2                 |
| 41                 | 11.9                |       |                     |



### Solution

Let's begin with the molecular ion peak, which appears at  $m/z = 86$ . Now compare the relative abundance of this peak and the  $(M+1)^+$  peak (which appears at  $m/z = 87$ ). The relative height of the  $(M+1)^+$  peak is 1.2% but be careful here. In this case,

the molecular ion is not the tallest peak. The tallest peak (base peak) appears at  $m/z = 43$ . The data indicate that the  $(M+1)^+$  peak is 1.2% as tall as the base peak. But we need to know how the  $(M+1)^+$  peak compares to the molecular ion peak. To do this, we take the relative height of the  $(M+1)^+$  peak, divide by the relative height of the  $(M)^+$  peak, and then multiply by 100%.

$$\frac{1.2\%}{20.9\%} \times 100\% = 5.7\%$$

the  $(M+1)^+$  peak is 5.7% as tall as the  $(M)^+$  peak.

Recall that each carbon atom in the compound contributes 1.1% to the height of the  $(M+1)^+$  peak, so we divide by 1.1% to determine the number of carbon atoms in the compound.

$$\text{Number of C} = \frac{5.7\%}{1.1\%} = 5.2$$

compound cannot have a fractional number of carbon atoms, so the value must be rounded to the nearest whole number, or 5.

The molecular weight is known to be 86, because the molecular ion peak appears at  $m/z = 86$ . Five carbon atoms equals  $5 \times 12 = 60$ , so the other elements in the compound must therefore give a total of  $86 - 60 = 26$ . The molecular formula cannot be  $C_5H_{26}$ , because a compound with five carbon atoms cannot have that many hydrogen atoms.

Therefore, we conclude that there must be another element present. The two most common elements in organic chemistry (other than C and H) are nitrogen and oxygen. It cannot be a nitrogen atom, because that would give an odd molecular weight (remember the nitrogen rule). So, we try oxygen. This gives the following possible molecular formula:



Q: Propose a molecular formula for a compound that exhibits the following peaks in its mass spectrum:

(a)  $(M)^+$  at  $m/z = 72$ , relative height = 38.3% of base peak

$(M+1)^+$  at  $m/z = 73$ , relative height = 1.7% of base peak

(b)  $(M)^{+\bullet}$  at  $m/z = 68$ , relative height = 100% (base peak)

$(M+1)^{+\bullet}$  at  $m/z = 69$ , relative height = 4.3%

(c)  $(M)^{+\bullet}$  at  $m/z = 54$ , relative height = 100% (base peak)

$(M+1)^{+\bullet}$  at  $m/z = 55$ , relative height = 4.6%

(d)  $(M)^{+\bullet}$  at  $m/z = 96$ , relative height = 19.0% of base peak

$(M+1)^{+\bullet}$  at  $m/z = 97$ , relative height = 1.5% of base peak

## Analyzing the $(M+2)^{+\bullet}$ Peak

Most elements have only one dominant isotope. For example, the dominant isotope of hydrogen is  $^1\text{H}$ , while  $^2\text{H}$  (deuterium) and  $^3\text{H}$  (tritium) represent only a small fraction of all hydrogen atoms.

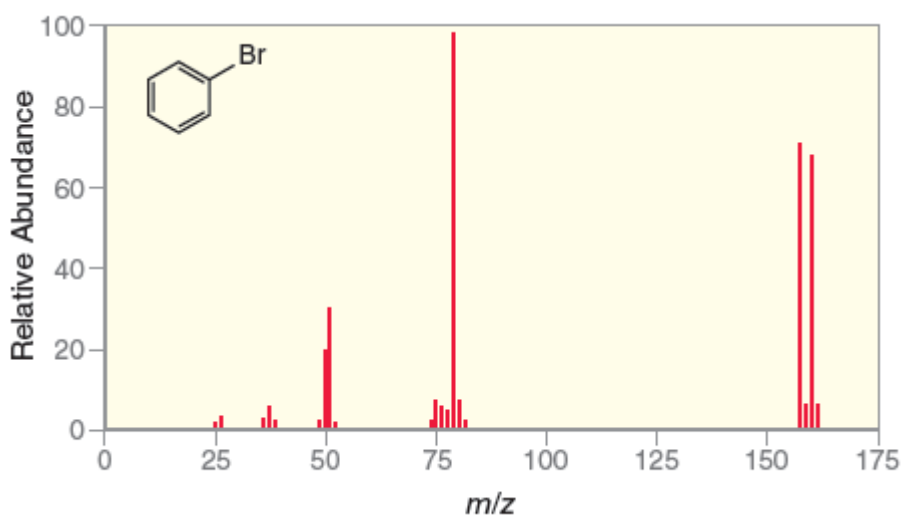
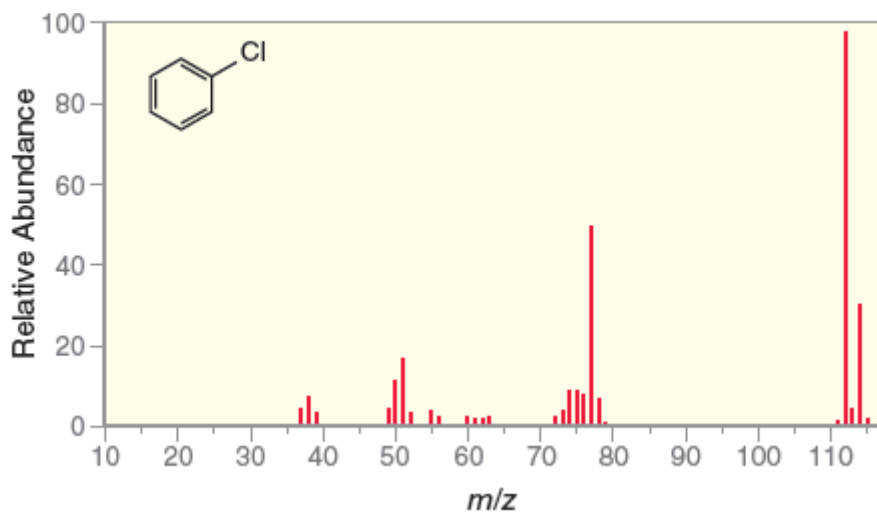
Similarly, the dominant isotope of carbon is  $^{12}\text{C}$ , while  $^{13}\text{C}$  and  $^{14}\text{C}$  represent only a small fraction of all carbon atoms. In contrast, chlorine has two major isotopes. One isotope of chlorine,  $^{35}\text{Cl}$ , represents

75.8% of all chlorine atoms; the other isotope of chlorine,  $^{37}\text{Cl}$ , represents 24.2% of all chlorine atoms. As a result, compounds that contain a chlorine atom will give a characteristically strong

## Analyzing the $(M+2)^{+\bullet}$ Peak

$(M+2)^{+\bullet}$  peak. For example, consider the mass spectrum of chlorobenzene. The molecular ion appears at  $m/z = 112$ . The peak at  $(M+2)$  ( $m/z = 114$ ) is approximately one-third the height of the parent peak. This pattern is characteristic of compounds containing a chlorine atom.

Compounds containing bromine also give a characteristic pattern. Bromine has two isotopes,  $^{79}\text{Br}$  and  $^{81}\text{Br}$ , that are almost equally abundant in nature (50.7% and 49.3%, respectively). Compounds containing bromine will therefore have a characteristic peak at  $(M+2)$  that is approximately the same height as the molecular ion peak. For example, consider the mass spectrum of bromobenzene



Below are mass spectra for four different compounds. Identify whether each of these compounds contains a bromine atom, a chlorine atom, or neither.

